Local Area Dynamic Routing Protocol: a Position Based Routing Protocol for MANET

ADAM MACINTOSH

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This thesis is dedicated to my parents and my loving wife Aras, without whose support and encouragement this work may not have been accomplished.

LIST OF FIGURES

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PUBLICATIONS

The content in this thesis is mainly based on research work done during PhD studies and that were published;

- A. Macintosh, M. Ghavami, and M. FeiSiyau"Lightweight Local Area Network Dynamic Routing Protocol for MANET ", International Journal of Soft Computing and Software Engineering [JSCSE], Vol. 2, No. 7, pp. 9-25, 2012, Doi: 10.7321/jscse.v2.n7.2.

- A. Macintosh, M. Ghavami, and M. FeiSiyau 'Local Area Network Dynamic (LANDY) routing protocol: A position based routing protocol for MANET", IEEE European Wireless. EW 18th European Wireless Conference, May 2012.

- Macintosh, A.; Ghavami, M.; Siyau, M.F., "Performance comparison of position based routing protocols using different mobility models," Wireless Conference (EW), Proceedings of the 2013 19th European , vol., no., pp.1,6, 16-18 April 2013

- Adam Macintosh, Mohammed Ghavami, Ming Fei Siyau, "Investigating the impact of speed on the performance of position based routing protocols in mobile ad hoc networks," International Journal of Research in Wireless Systems (IJRWS), Vol. 3, Issue No. 1, pp. 9 – 22, April. 2014

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ABBREVIATION

AODV	Ad-Hoc on Demand Distance Vector Protocol
BER	Bit Error Rate
CSMA	Carrier Sense Multiple Access
CSMA/CD	CSMA with Collision Detection
CSMA/CA	CSMA with Collision Avoidance
CMM	Column Mobility Model
CSMM	City- section mobility model
CCID	Cell Code Identifier
DSR	Dynamic Source Routing
DSDV	Dynamic Destination-Sequenced Distance Vector routing protocol
DCF	Distributed Coordination Function
DIFS	DCF Inter-Frame Space
DT	Delaunay Triangulation
DREAM	Distance Routing Effect Algorithm for Mobility
FSR	Fisheye State Routing Protocol
FAMA	The Floor Acquisition Multiple Access
FER	Frame Error Rate
FIFO	First-In, First-Out
FCS	Future Combat Systems
GRA	Geometric Routing algorithm (Face Routing)
GPS	Global Positioning Service
GLS	Grid Location Service
GPSR	Greedy Perimeter Stateless Routing

GRP	Geographical routing protocol
GMM	Gauss-Markov model
GG	Gabriel Graph
HWMP	Hybrid Wireless Mesh Protocol
IETF	Internet Engineering Task Force
LAR	Location Aided Routing
LLC	Logic Link Control
LC	Locomotion Components
MANET	Mobile Ad Hoc Network
MNS	Mobile Nodes
MPR	Multipoint Relaying
MACA	The Multiple Access with Collision Avoidance
MACAW	MACA for Wireless
MFR	Most Forward within R
MCID	Unique Code Identifier
MMM	Manhattan Mobility Mode
MM	Mobility model
MN	Mobile Node
MST	Minimum Spanning Tree
MAC	Media Access Control
NRL	Normalized Routing Load
NAVS	Network Allocation Vectors
NFP	Nearest with Forward Progress
NCMM	Nomadic Community Model
OPNET	Optimized Network Engineering Tools
OLSR	Optimized Link Status Routing

OSI	Open Systems Interconnection Model
PVRWM	Probabilistic Version of the Random Walk Mobility Model
PMM	Pursue Mobility Model
PDU	Packet Data Payload
QOS	Quality of Service
RFC	Request For Comments
RWM	Random Walk Model
RDM	Random Direction Model
RWpM	Random Waypoint Model
RPGM	Reference Point Group Model
RTS/CTS	Request to Send and Clear to Send
RREQ	Route Request
SNR	Signal to Noise Ratio
SIFS	Short Inter-Frame Space
SINR	Signal to Interference and Noise Ratio
STD	State Transition Diagrams
TDMA	Division Multiple Access
UDG	Unit Disk Graph
VTCSMA	Virtual time CSMA
WLAN	Wireless Local Area Networks
ZRP	Zone Routing Protocol

ABSTRACT

A Mobile Ad Hoc Network (MANET) comprises mobile nodes (MNs), equipped with wireless communications devices; which form a temporary communication network without fixed network infrastructure or topology.

The characteristics of MANET are: limited bandwidth; limited radio range; high mobility; and vulnerability to attacks that degrade the signal to noise ratio and bit error rates. These characteristics create challenges to MANET routing protocols. In addition, the mobility pattern of the MNs also has major impact on the MANET routing protocols.

The issue of routing and maintaining packets between MNs in the mobile ad hoc networks (MANETs) has always been a challenge; i.e. encountering broadcast storm under high node density, geographically constrained broadcasting of a service discovery message and local minimum problem under low node density. This requires an efficient design and development of a lightweight routing algorithm which can be handled by those GPS equipped devices.

Most proposed location based routing protocols however, rely on a single route for each data transmission. They also use a location based system to find the destination address of MNs which over time, will not be accurate and may result in routing loop or routing failure.

Our proposed lightweight protocol, ‘Local Area Network Dynamic Routing’ (LANDY) uses a localized routing technique which combines a unique locomotion prediction method and velocity information of MNs to route packets. The protocol is capable of optimising routing performance in advanced mobility scenarios, by reducing the control overhead and improving the data packet delivery.

In addition, the approach of using locomotion prediction, has the advantage of fast and accurate routing over other position based routing algorithms in mobile scenarios. Recovery with LANDY is faster than other location protocols, which use mainly greedy algorithms, (such as GPRS), no signalling or configuration of the intermediate nodes is required after a failure.

The key difference is that it allows sharing of locomotion and velocity information among the nodes through locomotion table. The protocol is designed for applications in which we expect that nodes will have access to a position service (e.g., future combat system). Simulation results show that LANDY`s performance improves upon other position based routing protocols.

CHAPTER 1. INTRODUCTION

1.1. Background

A MANET is made up of MNs, equipped with wireless communications devices, which form a network without a fixed infrastructure and topology Figure 1. This type of network is useful for a diverse range of applications, such as: emergency, military, sensors, personal networks, environmental monitoring and border security [1].

MANET is characterised by limited bandwidth, limited radio range, and vulnerability to conditions that degrade signal to noise ratio (SNR) and introduces high bit error rate (BER). MNs are mostly subject to power limitations and high mobility which introduces rapid topology changes. Also, unlike a fixed wired network; in MANET each node will participate both as an end node and as a router.

These characteristics lead to challenges in the design and implementation of MANET routing protocols, and have led to much research in this area [2].

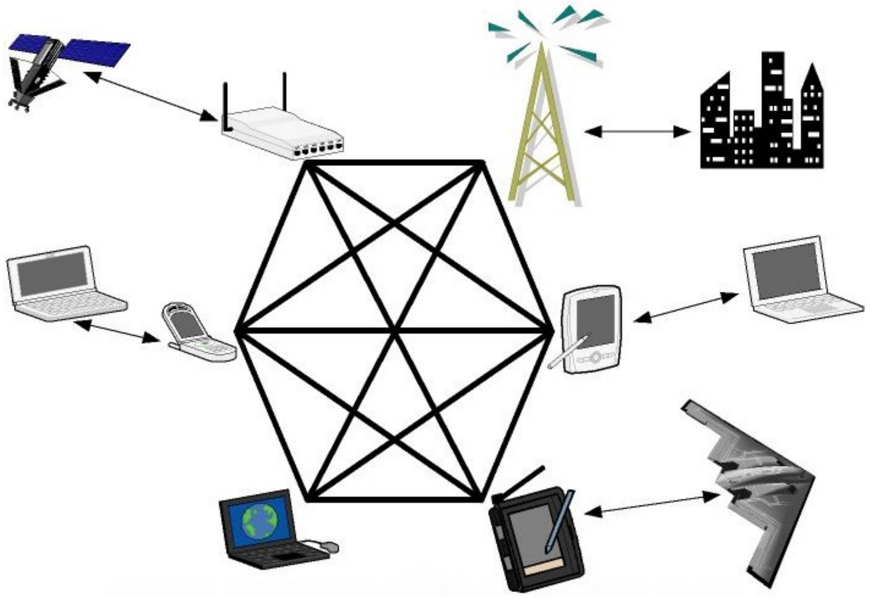


Figure 1. Wireless Ad hoc Networks

2.1. MANET Definition

Mobile networking is one of the most important technologies supporting advanced packet services and real-time applications. There are two different approaches for enabling wireless mobile units to communicate with each other:

1.1.1. Infrastructure

Wireless mobile networks have been based on the cellular concept and relied on good infrastructure, in which mobile devices communicate with access points (Base Stations) connected to the fixed network infrastructure. Examples of this type of wireless networks are GSM, UMTS, CDMA, and WLAN [3].

1.1.2. Ad Hoc

The infrastureless wireless mobile network is a group of wireless network nodes that temporarily form a network to exchange information without using any fixed network infrastructure. An example of this is a group of laptop computers formed into an ad hoc network for a temporary period of time, such as a conference meeting amongst a group. If the nodes are moving, this scenario is usually known a MANET.

1.2. MANET Characteristics

A MANET has the following features:

1.2.1. Wireless Communication

The MNs communicate with each other over a wireless medium. As this communications medium is a noisy and fading channel with interference, advanced modulation and coding schemes are required to enable stable data transmission [4]. Also, the medium is a shared channel, so multiple access protocols are essential to aid effective sharing of the channel among MNs.

1.2.2. Distributive Load

As there is no fixed network for the central control of the network operations, the control and management of the network must be shared amongst the MNs. The nodes involved in a MANET, should act as a team and a relay as needed, to support security and routing.

1.2.3. Independent Terminals

In a MANET, each MN is an independent node, which may function as both a host and a router. As well as the processing ability to send and receive data as a host, the MNs must also perform routine tasks. Typically in MANET, you cannot differentiate between MNs and routers.

1.2.4. Dynamic Network Topology

Since network nodes are moving, the shape of the network is not stable; therefore connectivity between the MNs will change over time. A MANET should adjust according to mobility patterns of the MNs, traffic and propagation conditions [5].

The MNs can communicate between each other while on the move, forming a temporary network. In addition, a node in MANET may function within the ad hoc network, and may access a fixed network (e.g. Internet).

1.2.5. Multi-hop Routing

Common ad hoc routing algorithms can be single-hop or multi-hop, depending on diverse link layer attributes and routing protocols. Single-hop MANET routing is simpler than multi-hop routing, in terms of protocol structure and operation [6].

However, the functionality and applicability are impaired. When data packets are being delivered from a source MN to a destination MN which is out of the transmission range, the packets should be forwarded via one or more intermediate MNs (gateway).

1.2.6. Variable Link Capacity

The high bit error rates of wireless connection, has a major effect on a MANET. One end-to-end path can be shared by multiple events. The channel over which the MNs communicate is subject to noise, fading and interference.

The wireless network has much more limited bandwidth compared to a wired network. In some scenarios, the path between any pair of MNs can navigate multiple wireless links and the link themselves can be various [7].

1.3. MANET Application

Ad hoc networking has grown in importance, supporting a wide range of applications as a result of a huge increase in portable devices and development of wireless communications.

Ad hoc networks can be deployed anywhere, where there is sparse or no communication infrastructure. Ad hoc networking allows the devices to maintain connections to the network, as well as easily adding and removing from the network [8].

The set of applications for MANETs is numerous, ranging from large-scale, mobile, highly dynamic networks (e.g., military tactical networks); to small, static networks that are limited by power sources (e.g., wireless sensor networks).

Such applications are:

1.3.1. Military Operations

Military hardware often contains computing equipment. Ad hoc networking allows military personal to use available network technology to maintain efficient communication between soldiers, vehicles, and military headquarters [9].

Military need created the basis for the current ad hoc networking. MANETs provide seamless and real-time communications in command, control, communications, computers, intelligence, surveillance, and future combat system (FCS).

1.3.2. Commercial

Ad hoc networks can be used in emergency operations for disaster relief efforts (e.g., natural disasters and accidents). Emergency rescue operations take place where there is no existing communications infrastructure or damaged and urgent deployment of a communication network is required [10].

Information is conveyed from one team member to another over small handheld network devices. Other commercial scenarios include vehicle to vehicle ad hoc mobile communication, etc.

1.3.3. Local Level

Ad hoc networks can independently link an instant and temporary multimedia network, using smart phones or notebooks to spread and share information at for example, a conference [11].

Another application might be in home networks, where devices can communicate directly to exchange information. Similarly, in other civilian environments such as; taxis, sporting events, sea and air transport.

1.3.4. Wireless Personal Area Network

A short range MANET can aid the intercommunication among several mobile devices such as a PDA, a laptop, and a smart phone [12].

Messy wired cables are replaced with wireless connections. Such an ad hoc network can also extend the access to the internet or other networks by mechanisms e.g. Wireless LAN (WLAN), GPRS, and UMTS.

1.3.5. Wireless Sensor Networks

In wireless sensor networks, the MANET consists of many lightweight sensor nodes that are closely placed near the phenomena of interest [13].

A sensor node has a sensing unit, a processing unit, a transceiver unit and a power unit to gather, process and analyse data; via a wireless network. Common sensor uses are military, health, transportation, traffic management, agriculture, environmental and disaster monitoring.

1.4. MANET Challenges and Major Issues

Despite its many positives, the features of MANET introduce several challenges and boundaries that must be researched before a wide commercial deployment can be implemented. These include:

1.4.1. Routing

Since the topology of the network is in flux, the issue of routing packets between any two nodes becomes a challenge. Most protocols are based on reactive routing instead of proactive routing [1, 2, 4, 6, 7,14].

The proactive routing procedure distributes routing information and performs routing calculation periodically, as the reactive routing procedure distributes the routing information and performs routing calculation only if there is a packet to be transmitted on request only.

The advantage of reactive routing is the reduced control overhead in a network with the topology in flux. However, reactive routing has longer end-to-end delay compared with proactive routing [15].

Multicast routing produces challenges as the multicast formation is no longer static due to the random mobility of MNs within the network. Routes between nodes may contain multiple hops, which is more complex than the single hop communication.

1.4.2. Security and Reliability

As well as the usual vulnerabilities of wireless connection, an ad hoc network has its specific security problems issues due to the broadcast nature of wireless transmission.

The feature of distributed operation requires a variety of schemes of authentication and key management. Wireless link characteristics cause reliability problems, because of the limited wireless transmission range, the broadcast nature of the wireless medium (e.g. hidden terminal problem), mobility induced packet losses, and data transmission errors [16].

1.4.3. Quality of Service

Delivering different quality of service (QoS) levels in an evolving environment will be a challenge. The inherent unpredictability of communications quality in a MANET makes it difficult to offer fixed guarantees on the services offered. An adaptive QoS must be implemented to support multimedia services.

1.4.4. Internetworking

As well as the communication within an ad hoc network, internetworking between MANET and fixed networks (IP based core network) is often anticipated.

The concurrence of routing protocols in such a mobile device introduces challenges for effective mobility management [17].

1.4.5. Power Consumption

For Many lightweight mobile devices, the communication related functions should be optimized for minimum power consumption. Most lightweight mobile devices are powered by batteries with a limited amount of energy.

It is obvious that battery life create constraints on the large scale deployment of mobile networks. Therefore, reducing power usage, is a vital prerequisite in routing protocol design [18].

1.5. Thesis Statement

My thesis in this dissertation, is that location based routing protocols, which does not rely on periodic techniques (network broadcast flooding), is more efficient and performs better than location based routing that utilise such techniques.

1.6. Research Contributions

This dissertation makes the following contributions:

- A detailed MANET routing protocols classification, reviewing location services, forwarding strategies, and run simulation for performance comparison between major routing protocols.

- A detailed investigation on the impact of MAC layer on the performance of MANET routing protocols.

- A detailed investigation on the impact of Physical layer on the performance of MANET routing protocols.

- Mobility Modelling: The modelling of mobility attempts to mathematically quantify the mobility characteristic with each mobile unite in dynamic topology.

- A detailed investigation on the impact of mobility models on the performance of MANET routing protocols. We investigated the fundamental factors ‘Speed’, ‘pause time’ and ‘minimum node degree’ which have a major impact on the performance of position based routing protocols under different mobility models.

  A comparative study of major position based routing protocols and mobility models are presented here. Both independent entity and dependent group mobility models have been selected.

  The effect of speed, pause time and minimum node degree on the performance of protocols under each of the chosen mobility models is analysed, deriving an analytical theorem for the required transmission range in connected ad hoc networks.

- A detailed comparative performance evaluation of reactive and proactive routing protocols (DSR, OLSR, AODV and DSDV which explores the effectiveness of different proactive and reactive routing algorithms in a wide range of ad hoc network simulation scenarios.

- LANDY routing algorithm: The LANDY routing algorithm is developed to find the most stable route for many possible candidates that can last longer. If a route that lasts longer is kept during the communication between the source and destination nodes, it doesn't need to spend extra resources to switch route.

  Also to address the broadcast storm under 'high node density, local minimum problem under low node density, and the geographically constrained broadcast of a service discovery message. The protocol is capable of optimising routing performance in advanced mobility scenarios, by reducing the control overhead and improving the data packet delivery.

- LAWAND right hand rule algorithm: The LAWAND right hand rule algorithm is developed to address these two issues (right hand rule may miss a perimeter path in a specific network graph, and right hand rule may follow a degenerate path) and always follows a proper perimeter when given the exact position of nodes.

  Using simple geometric forms we prove the new technique finds the shortest perimeter of an obstacle in the network.

- Probability of communication process: A new metric for measuring routing performance between active MNs. The measurement based on the assembled paths over randomised dynamic network topologies.

- A comprehensive comparative performance evaluation of LANDY, GPSR, and GRP which explores the effectiveness of different location based routing algorithms in a wide range of ad hoc network simulation scenarios.

- A comprehensive investigation of the impact of unidirectional links on location based routing characteristics of ad hoc network.

- The first investigation of the impact of unidirectional links on location based protocols performance in ad hoc networks.

- Evaluation and Simulation: Simulation is performed using OPNET to evaluate the feasibility of the proposed routing algorithms.

1.2. Dissertation Organization

To Support my thesis statement, in this dissertation, I present the design and evaluation of a new location based routing protocol, local area dynamic routing protocol (LANDY) for wireless ad hoc networks.

LANDY uses no periodic control packet network wide floods, or periodic neighbours sensing, and adapts its behaviour based on network conditions and application sending pattern, allowing efficient detection of broken links and expiration of routing state that is no longer needed.

Our proposed lightweight protocol LANDY, uses a localized routing technique which combines a unique locomotion prediction method and velocity information of MNs to route packets.

The protocol is capable of optimising routing performance in advanced mobility scenarios, by reducing the control overhead and improving the data packet delivery. In addition, the approach of using locomotion prediction has the advantage of fast and accurate routing over other position based routing algorithms in mobile scenarios.

Recovery with LANDY is much faster than other location protocols which use mainly greedy algorithms, (such as GPRS), no signalling or configuration of the intermediate nodes is required after a failure. The key difference is that it allows sharing of locomotion and velocity information among the nodes through locomotion table.

We demonstrate that LANDY works well in variety of simulation scenarios, and compares well against protocols that utilise proactive mechanisms and generate significantly lower packet overhead.

The protocols that I have chosen to compare LANDY against are, Greedy Perimeter Stateless Routing (GPSR) and Geographical routing protocol (GRP).

These two protocols represent two different design points in location based protocol design space, are well documented, and have been shown to perform well in previous studies. Also, we developed a new right hand rule algorithm to address these two issues (right hand rule may miss a perimeter path in a specific network graph, and right hand rule may follow a degenerate path), and always follows a proper perimeter when given the exact position of nodes. Using simple geometric forms we prove the new technique finds the shortest perimeter of an obstacle in the network.

In addition, in this dissertation, I study the impact of unidirectional links on the routing characteristics of ad hoc networks, and use this study to explore the effect of unidirectional links on location based routing performance.

Using the lessons learned from this work, I extended LANDY with mechanisms that enable it to route over unidirectional links, and show that the unidirectional extension improve the performance of the protocol by increasing packet delivery ratio and decreasing overhead. Finally we present a new metric (Probability of Communication Process) for measuring routing performance between active MNs. The measurement based on the assembled paths over randomised dynamic network topologies using “Sobol sequence” algorithm.

This dissertation consists of ten chapters. As the introduction, chapter 1 has described the background and overview of MANET routing, and discussed the current issues of MANET position based routing protocols and our contributions. Chapter 2 presents a detailed MANET routing protocols classification and techniques, and run simulation for performance comparison between major proactive and reactive routing protocols.

Chapter 3 presents a detailed investigation on the impact of MAC layer on the performance of MANET routing protocols. And run simulation for performance comparison between major routing protocols under different MAC protocols. Chapter 4 presents a detailed investigation on the impact of Physical layer on the performance of MANET routing protocols. And run simulation for performance comparison between major routing protocols under different Physical layer.

Chapter 5 presents a detailed investigation on the impact of mobility models on the performance of MANET routing protocols. We investigated the fundamental factors ‘Speed’, ‘pause time’ and ‘minimum node degree’ which have a major impact on the performance of position based routing protocols under different mobility models. And run simulation for performance comparison between major routing protocols under different mobility models.

Chapter 6 presents LANDY routing protocol design and processes. A detailed MANET routing protocols comparison, reviewing location services, forwarding strategies.

Chapter 7 present the implementation details of LANDY routing protocol, and the LANDY model in OPNET. Also, we introduce a new measurement method called:

Probability of Communication Process. This method is used to measure the success rate of an established path by a MANET routing protocol using Sobol sequence algorithm. In addition, we run simulation for performance comparison and analysis on impact of route, link, and mobility models.

Chapter 8 provides the simulation results for real time scenarios. Our experiment consists of three parts. In experiment 1, we simulate a mobile network with low movement factor in order to compare LANDY and the major position based routing protocols.

In experiment 2, we simulate a general network with obstacles and fairly large movement factor. In experiment 3, we simulate a real-world environment with some relatively slow nodes and some very fast nodes. In each experiment, our novel techniques are compared to GPSR and GRP.

The scenarios mainly test the protocols: Ability to respond to local changes for long links, ability to cope with large volume of traffic, message overhead with low mobility factor, ability to respond to fast link changes and fluctuating traffic, message overhead with constant topology updates, ability to work with both slow and fast changing network topologies, and ability to cope with network partitioning. Chapter 9 and 10 concludes the thesis with a short summary and future work.

CHAPTER 2. MANET ROUTING PROTOCOLS AND TECHNIQUES

It is accepted by the research community, that routing strategy is the most important research problem. Determining the efficient routing paths and delivering messages in an ad hoc environment where the network topology changes, is far less researched. New prototypes are needed to describe the mobile ad hoc feature of wireless networks, and new algorithms are required to effectively and efficiently route data packets to mobile destination in order to support various multimedia applications [19].

Aspects such as inconstant wireless link quality, propagation path loss, fading, interference, power consumption and mobility become major issues that add complexity to routing protocol design. Numerous routing protocols have been proposed with the forum of Internet Engineering Task Force (IETF) working documents of both Internet Drafts and Request For Comments (RFC). Many projects related to different features of MANETs have been researched by academics and institutes worldwide and results have been published [20].

It is acknowledged that routing protocols designed for wired networks are not effective for MANET. Those protocols, such as Open Shortest Path First (OSPF), are designed for stable, static infrastructures. Distance Vector and Link State routing algorithms are used in wired networks Table 1. They both flood information about the entire network topology to all network nodes on a periodic basis.

Table 1. MANETs Routing Algorithms

	Reactive protocols	**Proactive protocols**
Link state Protocols	DSR, TORA	OLSR,TBRPF, TORA, LANMAR/FSR
Distance Vector Protocols	AODV	

Distance Vector routing, a distributed Bellman-Ford algorithm, maintains the distance vectors to all destination nodes. The Link State routing algorithm, a Dijkstra shortest path algorithm, floods the link status to all nodes, allowing each to compute the shortest path to all destinations. When the network is in flux and participating nodes increase, these routing algorithms can generate routing loops due to degraded information [21].

In addition, a high volume of control overhead messages will be created, which will reduce the effectiveness of data transmission.

Many MANET routing protocols have been developed. These routing protocols are categorised as topology based routing protocols and position based routing protocols Figure 2.

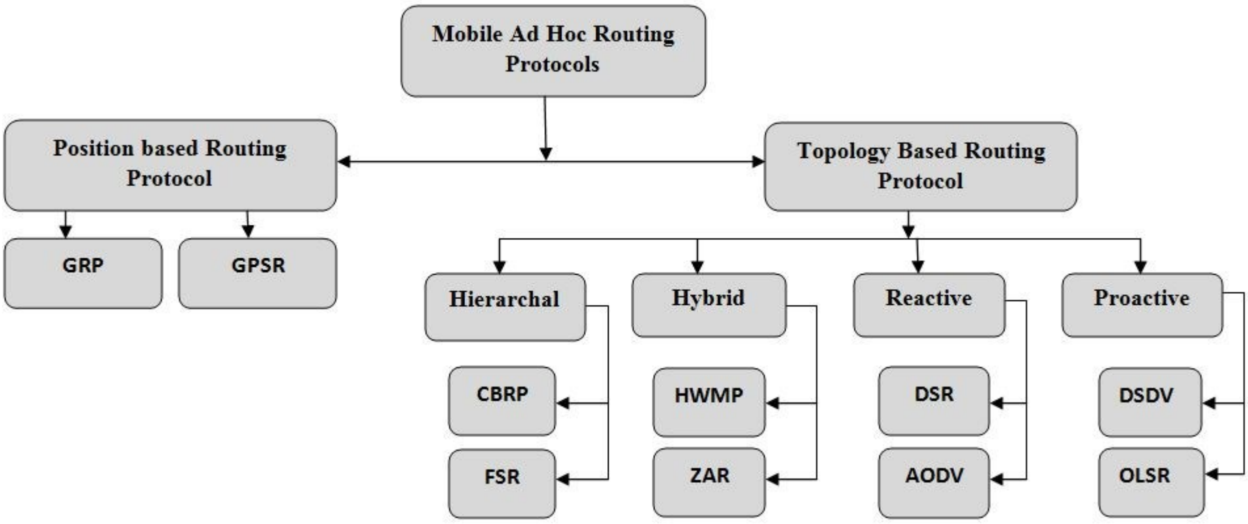


Figure 2. Mobile Ad hoc Network Routing Protocols Classification

2.1. Topology Based Routing Protocol

Topology based routing performs packet routing based on information about network links, while position based routing uses physical location information about the participating nodes to make decisions on how to route packets [22].

The topology based routing algorithms often use flooding to distribute network topology information, which will increase the control overhead traffic that reduces the bandwidth available. One technique to reduce the control overhead is ‘caching’. This may still produce high volume of overhead as result of dynamic changes in network topology. Topology based routing can be further categorised into proactive, reactive and hybrid approaches.

2.1.1. Proactive Routing Protocol

Proactive or table driven routing algorithms (connection oriented algorithm): In this type of algorithm, the routing table is periodically updated via message broadcasting among all MNs. The advantage of this type of algorithm is that data packet broadcast is efficient because an end to end route is always available; but the disadvantage is the high overhead in maintaining routing table and waste of network bandwidth [23].

Routing protocols such as Routing Information Protocol (RIP) and OSPF are both proactive routing protocols.

Periodic broadcast of network topology updates (e.g., distance vector or link state information) is required to compute the shortest path from the source to every destination node, which uses a lot of bandwidth. While they are widely used in the internet backbone, they cannot be used in the MANET directly, because of the limited bandwidth and dynamically changed network topology of the MANET [24].

These protocols are less efficient under a high volume of control overhead, as a result of the necessity to distribute network topology and route path maintenance. Many proactive routing protocols have been proposed to improve the control overhead, such as Highly Dynamic Destination-Sequenced Distance Vector routing protocol (DSDV) and Optimized Link Status Routing (OLSR).

2.1.1.1. Highly Dynamic Destination-Sequenced Distance Vector Routing Protocol

DSDV is a proactive routing protocol for MANETs. It was presented by C. Perkins and P. Bhagwat, based on the Bellman-Ford algorithm. The main objective of this algorithm was to address routing loop problems. Each entry in the routing table contains a series of numbers, the numbers are even if a link is present, otherwise it is odd. The number is produced by the destination node, and the sender needs to transmit the next update with its number attached. Routing information is distributed throughout the network by transmitting complete dumps, and incremental updates frequently [25].

If a router receives updated information, then it uses the latest updated sequence number. If the series number is the same as the one already in the routing table, the route with the better metric is chosen, and expired numbers are deleted. DSDV needs frequent updates to maintain its routing tables, which impose constraints on battery power and bandwidth even when the network is not in use. A new series number is needed when topology of the network changes. Thus, DSDV is not suitable for highly dynamic networks.

2.1.1.2. Optimized Link State Routing Protocol

OLSR was proposed as part of Hipersom Project. OLSR is intended for large and dense MANETs. It is based on a Multipoint Relaying (MPR) flooding method to reduce the message control overhead. In this approach, every node in the network broadcasts HELLO messages that contain one-hop neighbour information, periodically. If the time to Live (TTL) of HELLO messages is 1, then the messages are not forwarded by its neighbours. HELLO messages allow every node to obtain local topology information.

A selector node chooses a subset of its neighbours to act as gateway nodes to pass the information. The MPR nodes periodically broadcast its selector list throughout the MANET via MPR flooding, therefore every node in the network knows by which gateway node, every other node can be reached [26].

2.1.2. Reactive Routing Protocol

Reactive or on demand routing algorithms (connection oriented algorithm): In this type of algorithm the route is only established before data packet transmission. The advantage of this type of algorithm is message broadcast occurs only on route discovery to prevent broadcast storm; and the disadvantage is the end to end delay caused by the route maintenance which is higher than in the proactive algorithm.

Reactive routing algorithms initiate routing discovery only when packet forwarding is required and maintain only active route. This algorithm reduces the control overhead. Two major reactive routing protocols are Dynamic Source Routing (DSR) and Ad-Hoc on Demand Distance Vector Protocol (AODV) .

In reactive routing protocols, the procedure is divided into the following two steps: "*Route discovery and Route maintenance*".

(1) Route discovery: Route discovery procedure in reactive protocols is similar to that in hardwired routing protocols.

In a hardwired network, before the source node sends date to destination node, it broadcasts an Address Resolution Protocol (ARP) request packet to all the other nodes attached to the LAN to get the MAC address of destination. In MANET the route discovery works in the IP layer, and it takes into consideration nodes out of the source wireless transmission range.

In MANET, if the source does not have up to date path to the destination node in its routing table, it broadcasts a route discovery packet throughout the network to establish the route between itself and the destination. Intermediate nodes along the path forward the discovery packet and update its routing table to identify the route [27].

(2) Route maintenance: When the route between the source and destination node has been established, route maintenance is implemented to check the legitimacy of the route because the nodes along the path may move randomly, or shut down due to power drainage.

If link failure is discovered along the path during the route maintenance, the source node will be notified and may initiate route discovery to find an alternative route, or launch a local repair.

2.1.2.1. Ad hoc On-demand Distance Vector

AODV is reactive routing protocol. AODV has the following procedures:

(1) Route discovery: If the route to the destination is not available in the routing table, a Route Request packet is broadcast throughout the MANET. On arrival of the route request, the node creates a reverse routing entry back to the source of route request, which is used to forward replies [28].

The destination or the intermediate node, which has a valid route, replies with a route reply unicast packet. On receipt the route reply, the reverse routing path to the source node of route reply is also created, similar to the processing of route request. Linked to each routing entry is a source list, which is created at the same time.

(2) Route maintenance: All the nodes participating in an active route, periodically broadcast HELLO messages to their neighbours.

If the node does not receive a HELLO message or a data packet from neighbours for a period of time, the link between itself and its neighbours is declared broken. If the destination node is not reachable within the next hop, local repair mechanism may be launched to rebuild the route towards the destination, otherwise the link fails [29].

2.1.2.2. Dynamic Source Routing

DSR is another reactive routing protocol. Unlike other unicast routing protocols, DSR does not maintain the routing table, it uses the source routing option in data packets. DSR uses route cache, which store the complete list of IP addresses of the nodes along the active path to the destination.

During route discovery phase, if the intermediate node has the route towards the destination in its routing cache, it can respond with a route reply packet and send a route reply about the source to the destination simultaneously.

DSR allows multi-paths, and if the source node receives a route error packet, it can use a path stored in the routing cache table, thereby saving the overhead of route discovery.

If the intermediate node discovers a downstream broken link during data packet forwarding, but no other path to the source node is available towards the same destination, then it forwards the packet along a new route, which is called packet salvaging [30].

2.1.3. Hybrid Routing Protocol

Hybrid schemes (connection oriented algorithm): This type of algorithm tries to include the advantages of the proactive and reactive algorithms however, it also includes the disadvantages of both algorithms, which is the control overhead and the end to end delay. Hybrid routing algorithms, such as the Zone Routing Protocol (ZRP) and Hybrid Wireless Mesh Protocol (HWMP).

2.1.3.1. Zone Routing Protocol

ZAR was the first hybrid routing protocol, with both reactive and proactive component. ZAR was proposed to reduce the control overhead of proactive routing protocol, which is caused by message broadcasting and reduce the end to end delay which is generated during the route discovery process in reactive routing protocol [31].

ZAR integrate local proactive routing and global reactive routing to achieve a higher level of efficiency and scalability. However, it still requires route maintenance. The boundary between local and global region limits distribution efficiency of information about network topology changes.

ZAR implement the multicast mechanism ‘Bordercast’ to generate route requests throughout MANET, instead of depending on neighbour broadcast flooding which is common in reactive algorithms. Therefore, ZAR is reliable protocol for multichannel routing and high load process [31].

2.1.3.2. Hybrid Wireless Mesh Protocol

HWMP was proposed based on AODV and tree based routing techniques. In mesh network topology all nodes are connected to each other (full mesh) or, almost each other (partial mesh). HWMP depends on peer link management protocol by which each mesh point discover and track neighbouring nodes.

HWMP is hybrid, because it supports two ways of path selection. The advantages of HWMP are covering large scale network, if one node becomes busy, it will redirect the traffic to another node, adaptively and reliably [32].

2.1.4. Hierarchal Routing Protocol

Hierarchal routing protocol was introduced for large skill networks. Numerous schemes have been proposed.

The procedure of hierarchical routing is arranging routers in a hierarchical way. Considering alternative method with every node connected to all other nodes, or if every node was connected to two nodes, shows the flexibility of hierarchical routing.

It minimises the complexity of network topology, improving routing efficiency, and creating much less congestion because of less routing message broadcast. With hierarchical routing, only central nodes connected to the backbone are aware of all paths. Nodes that lie within a region only know about paths in this region. Unknown destinations are delivered to the default route [33].

2.1.4.1. Cluster Based Routing Protocol

Cluster Based Routing Protocol (CBRP) was proposed to decrease average end-to-end delay and improve the average packet delivery ratio.

CBRP uses clustering structure and it divides the nodes of ad hoc network into a number of interconnecting or disjoint 2-hop- diameter clusters in a distributed manner.

Each cluster has a cluster head (CH) as controller within the substructure. Each CH acts as a temporary backbone within its zone and communicates with other CHs. By clustering nodes into groups, CBRP efficiently improves and reduces the flooding traffic through route discovery process [34].

2.1.4.2. Fisheye State Routing protocol

Fisheye State Routing Protocol (FSR) was proposed for high mobility and large scale MANETs. The name and idea originates from fish eyes. Fish eyes get a high resolution portrait about the object close by, while the resolution reduces when the object moves farther. In FSR, the source node only requires to know basic information about the direction towards the ultimate destination. The intermediate nodes will amend the packet’s movement on journey from the source to the destination node. FSR procedure as below:

(1) For a particular node (source node), the entire network is segmented into different scopes based on the distances (i.e., hops) of other nodes related to it.

(2) The link state updates are broadcast to the neighbouring nodes within the scopes (region).

The routing records matches to the nodes in a different region, and sent at diverse frequencies. The routing records towards the nodes in the inner region are sent at the maximum frequency, the other records are sent at a lower frequency [35].

Hence, the nodes close by will obtain more up to date link state updates, but the node far away may have inaccurate outdated link state information. FSR don't flood the network with link state updates, instead it exchanges the update between neighbouring nodes, which also aid the neighbours discovery process.

When the source need to find a path toward a destination node, it uses the most up to date link state information to compute the shortest path. Link state information is broadcast periodically only in order to reduce routing traffic overhead [36].

2.2. Position Based Routing Algorithms

Position based algorithms (connectionless algorithm): This type of algorithm overcomes the problem related to the maintenance of the routing table in connection oriented algorithms , where the performance degrades quickly when there is an increase in the number of MNs or the speed (dynamic changing).

Although a connectionless algorithm has no route manipulation for data transmission, it still encounters three problems. A) Broadcast storm under high node density. B) Local minimum problem under low node density. C) The geographically constrained broadcast of a service discovery message.

Position based routing algorithms eliminate some of the limitations of topology based routing, by using geographical information about the mobile nodes to make decision about routing packets. This position information is obtained by position service and location service [37].

Global Positioning Service (GPS) is an example of a position service which provides information about the position of the source node. Grid Location Service (GLS) is an example of a location service, which provides information about the position of the destination node.

If a MN wants to send data to a destination node, it will make a routing decision based on the destination and the positions of the source one hop neighbours. Consequently, position based routing protocol do not require route establishment or maintenance. Position information only needs to be distributed in the local area.

2.2.1. Greedy Perimeter Stateless Routing

GPSR proposed by Karp and Kung (2000) is a position based routing algorithm. GPSR makes greedy forwarding decisions using only information about the position of immediate neighbours in the network topology.

Packets are forwarded to the next-hop node which moves the packet the most ‘toward’ the position of the destination. By keeping only local topology information, GPSR scales better than topology based routing as the number of network destinations increases [38].

If the packet reaches a region where greedy forwarding is impossible, the algorithm enters into recovery mode by routing around the perimeter of the region. The disadvantage of GPSR is the control overhead and slow recovery process.

2.2.2. Geographical Routing Protocol

Routing in GRP is based on the shortest geographical distance between source and destination. Each node within a geographical area uses GPS to identify its own position.

GRP uses quadrants (neighbourhoods) to optimise flooding, it initiates network wide flooding to identify all nodes in the network. The disadvantage, is heavy control overhead when there are RREP [39].

2.2.3. Location Aided Routing

Location Aided Routing (LAR) [6] is another position based routing algorithm .The central point of LAR is the limited flooding of routing request packets in a small group of nodes which belong to a so-called request zone.

Two different schemes are brought to construct the request zone: (A) a rectangular request zone which contains the location of source and the expected zone of the destination; or (B) the group of the nodes closer to the destination than the source.

2.2.4. Geometric Routing Algorithm (Face Routing)

Face Routing [10] is a similar routing algorithm to GPSR. Face routing employs a similar planar graph traversal recovery approach when packet forwarding, to recover from local minima situations.

2.2.5. Beaconless Routing (Beacon-Less Routing Algorithm)

Traditional greedy forwarding mechanisms need periodic HELLO messages (beaconing), transmitted with maximum signal strength by each node in order to provide current position information about all one-hop neighbours [4, 40].

2.2.6. Geographical Routing Algorithm

The assumption in GRA [8] is that every node knows the position of itself, the destination and all its neighbours stored in the routing table at each node.

2.3. Ad hoc Network Routing Protocols Comparison

So far, the protocols have been analysed theoretically. Table 2 summarises and compares the results from these theoretical/qualitative analyses and shows what properties the protocols have and do not have [41].

As it can be seen from Table 2, none of the protocols support power conservation or QoS. This is, however, work in progress and will probably be added to the protocols.

All protocols are distributed, thus none of the protocols is dependent on a centralized node and can therefore easily reconfigure in the event of topology changes. DSDV is the only protocol that has most in common with traditional routing protocol in wired networks.

The sequence numbers were added to ensure loop-free routes. DSDV will probably be good enough in networks, which allows the protocol to converge in reasonable time. This however means that the mobility cannot be too high. The authors of DSDV came to the same conclusions and designed AODV, which is a reactive version of DSDV. They also added multicast capabilities, which will enhance the performance significantly when one node communicates with several nodes.

The reactive approach in AODV has many similarities with the reactive approach of DSR. They both have a route discovery mode that uses request messages to find new routes. The difference is that DSR is based on source routing and will learn more routes than AODV. DSR also has the advantage that it supports unidirectional links.

DSR has, however, one major drawback and it is the source route that must be carried in each packet. This can be quite costly, especially when QoS is going to be used.

ZRP and CBRP are two very interesting proposals that divide the network into several zones/clusters. This approach is probably a very good solution for large networks. Within the zones/clusters they have a more proactive scheme and between the zones/clusters they have a reactive scheme that have many similarities with the operation of AODV and DSR [42].

They have, for instance, a route discovery phase that sends requests through the network. The difference between ZRP and CBRP is how the network is divided. In ZRP all zones are overlapping and in CBRP clusters can be both overlapping and disjoint.

Table 2. Characteristics Comparison between Ad-hoc Routing Protocols

Routing characteristics	DSDV	AODV	DSR	OLSR
Loop-free	Yes	Yes	Yes	Yes
Multiple routes	No	No	Yes	No
Requires reliable or sequenced data	No	No	No	No
Periodic broadcasts	Yes	Yes	No	Yes
Power conservation	No	No	No	No
Security	No	No	No	No
Multicast	No	Yes	No	No
QoS Support	No	No	No	No
Unidirectional link support	No	No	Yes	No
Reactive	No	Yes	Yes	No
Distributed	Yes	Yes	Yes	Yes

None of the presented protocols are adaptive, meaning that the protocols do not take any smart routing decisions when the traffic load in the network is taken into consideration.

As a route selection criteria, the proposed protocols use metrics such as shortest number of hops and quickest response time to a request. This can lead to the situation where all packets are routed through the same node, even if there exist better routes where the traffic load is not as large [43].

2.4. Simulation Setup and Results

It is important to evaluate and compare the performance of different MANET routing protocols applied to FCS scenarios and incorporating more advanced mobility models.

FCS was the United States Army's major innovation program in 2003. FCS was intended to create new divisions equipped with new managed and unmanaged vehicles linked by an unprecedented fast and flexible battlefield network. The FCS was considered as a family of 18 combat vehicles, aircraft and weapon systems, all anticipated to work and communicate with each other through the battlefield in a “seamless network [71].

The protocols used in the experiments are DSR, OLSR, DSDV and AODV. We have selected these protocols to include reactive and proactive in our comparison. The number of nodes in the network simulation, are 50 and 100 nodes. Each MN has a nominal 300m radio transmission range with a free space path loss model.

The nodes are initially distributed randomly in the square mobility region. The simulation period is 1200 seconds and all nodes start moving at 10 seconds. The maximum speed of the random waypoint model (RWpM) is set to 30 m/sec.

Each CBR flow sends traffic at 100 kbps to a random destination. This dense network topology with a high mobility motion and a maximum speed of 30 m/sec provides high mobility scenarios. Each scenario performs ten simulation runs with different random seeds, and the mean of the metrics are compared [44].

In our simulation, we start MANET routing protocol after a specific random movement time, which is the simple solution to avoid the initialisation problem. The common parameter setting of the simulation is shown in Table 3.

There are different kinds of parameters for performance evaluation of routing protocols in MANET. These parameters have a different impact on overall network performance. Three important parameters will be evaluated in this research for overall network performance.

These parameters are end to end delay, throughput and delivery ratio. The MANET network simulations are implemented using OPNET Modeller simulation tool. In each simulation scenario, the nodes are initially located at the centre of the simulation region. The traffic destination is a random node.

Table 3. Simulation Parameters - Topology Based Routing Protocol

Parameters	Value
Simulation Area	1500 x 1500 sq.meters
Mobility Models Used	RWpM
Maximum Speed	30 m/sec
Antenna type	Omni antenna
Traffic model	CBR
Transmitter range	300 m
Bandwidth	2MB
MAC Protocols	IEEE 802.11
Data traffic size	512 bytes
Data packet rate	100 kbps
Simulation time	1200 sec
Number of Nodes	50, 100
Simulation software	OPNET

2.4.1. Performance Metric

The performance evaluation, as well as the design and development of routing protocols for MANETs, requires additional parameters. We have selected the following metrics to be collected during the simulation in order to evaluate the performance of the different protocols.

2.4.1.1. Delay

The end-to-end delay of packet is the time of generation of a packet by the source node up to the destination node; so this is the time that a packet takes to go across the network.

This time is expressed in seconds, therefore, all the delays in the network are called packet end-to-end delay, like buffer queues and transmission time.

2.4.1.2. Throughput

Throughput is defined as the ratio of total data that reaches a destination node from the source node. The time it takes the destination node to receive the last message is called throughput. Throughput is expressed as bytes or bits per sec (byte/sec or bit/sec).

2.4.1.3. Delivery ratio

The delivery ratio is the ratio of the number of successfully delivered data packets to the number of total data packets. It is the metric of the data transmission reliability.

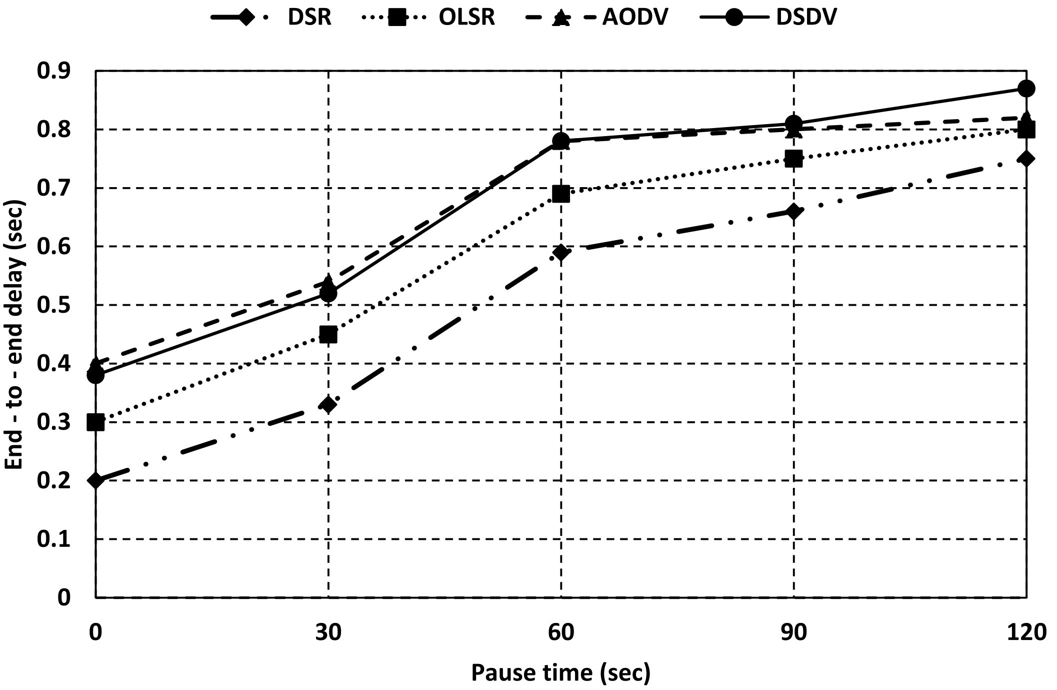
2.4.2. Simulation Result

In our simulations, four MANET routing protocols (DSR, AODV, DSDV and OLSR) were evaluated with Random Waypoint mobility models.

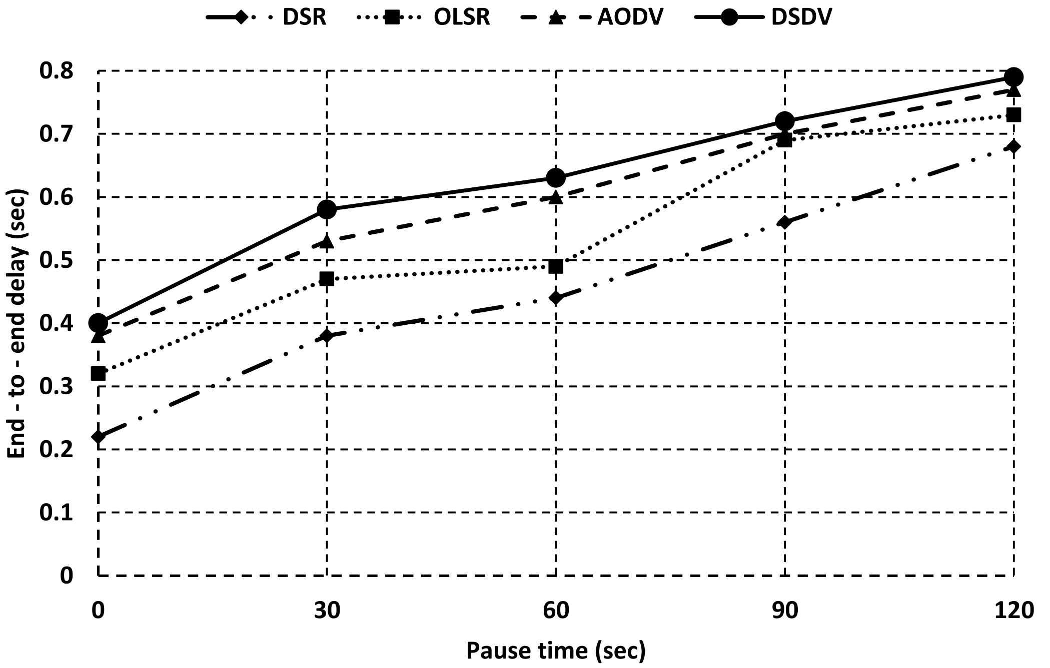
2.4.2.1.End-to-end Delay

The end-to-end delay time is massively affected when network speed is at a slow rate. As a result of little or no mobility of nodes, error occurs in the entire path and so there is a greater chance that it searches paths consisting of the same nodes.

In this case it cannot be effective, even if it selects a path taking mobility in to consideration. In end -to-end delay scenario, a poorer performance is expected when the number of nodes are fewer than 50, because longer routes might be designated instead of the shortest path.



(a) 50 nodes



(b) 100 nodes

Figure 3. End-to-end Delay for Random Waypoint Model

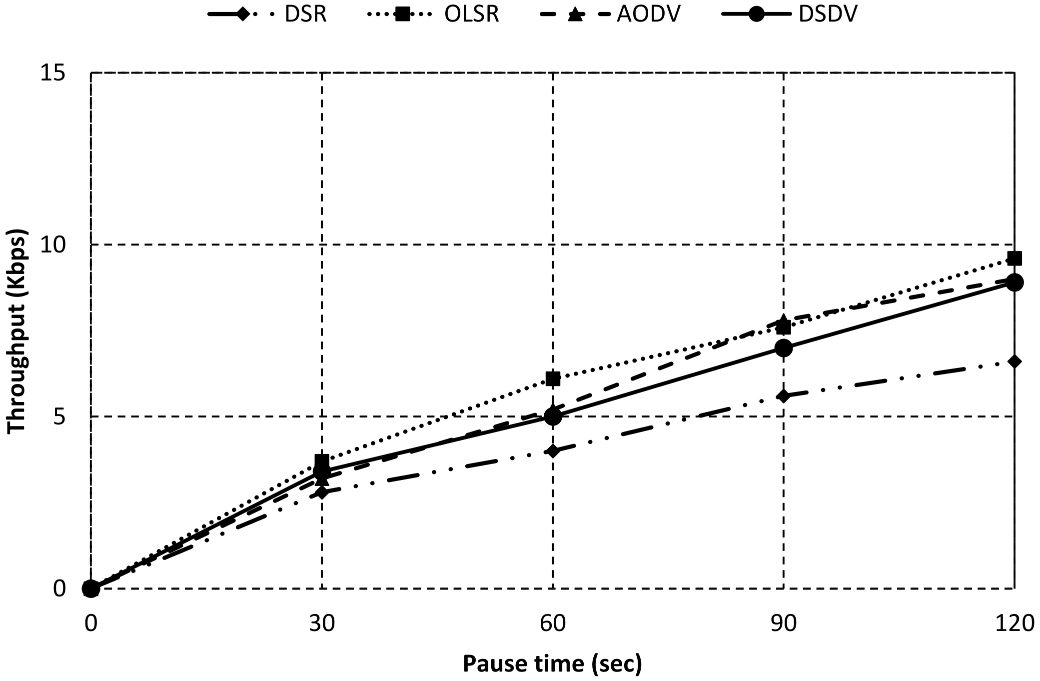
The end-to-end delay is lower in the case where more than one route is available. Figure 3 shows the end-to-end delay of DSDV, AODV, OLSR and DSR. The error bars indicate 90% confidence intervals.

Since DSR searches the current position of MN, it searches the path from the source to the destination node faster than AODV. Therefore, the end-to-end delay of DSR is lower than DSDV, OLSR and AODV.

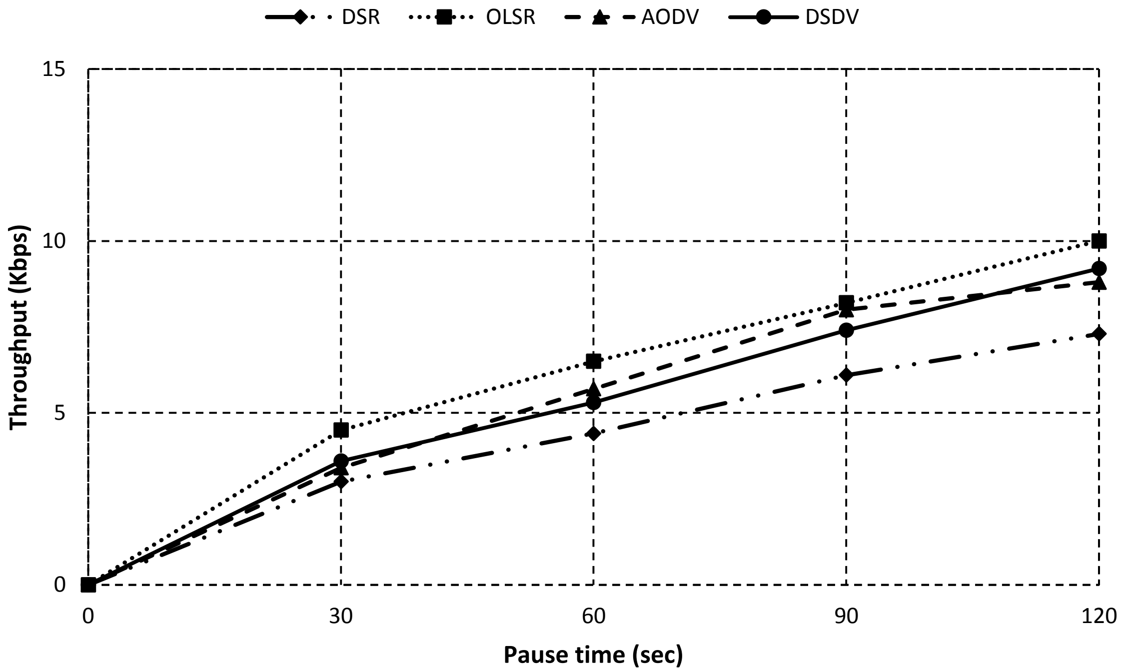
2.4.2.2.Throughput

The rate of packet throughput increases slowly depending on the node number increase in all protocols (DSR, DSDV, OLSR and AODV). As shown in Figure 4, there is a slight difference between OLSR and AODV in both scenarios. AODV had slight increases in the rate of packet throughput.

Although the performance improvement is not large, it makes a distinct appearance when the pause time is more than 90 sec. The more a node changes, the more nodes that consist of a link are changed, and link error can occur frequently. Therefore, OLSR packet processing ratio improves upon DSDV, DSR and AODV, in setting the shortest path. DSR packet ratio is lower due to link errors increasing as a result of faster node movement, but in OLSR packet throughput is decreased little, when the maximum velocity of nodes is 30 m/sec.



(a) 50 nodes



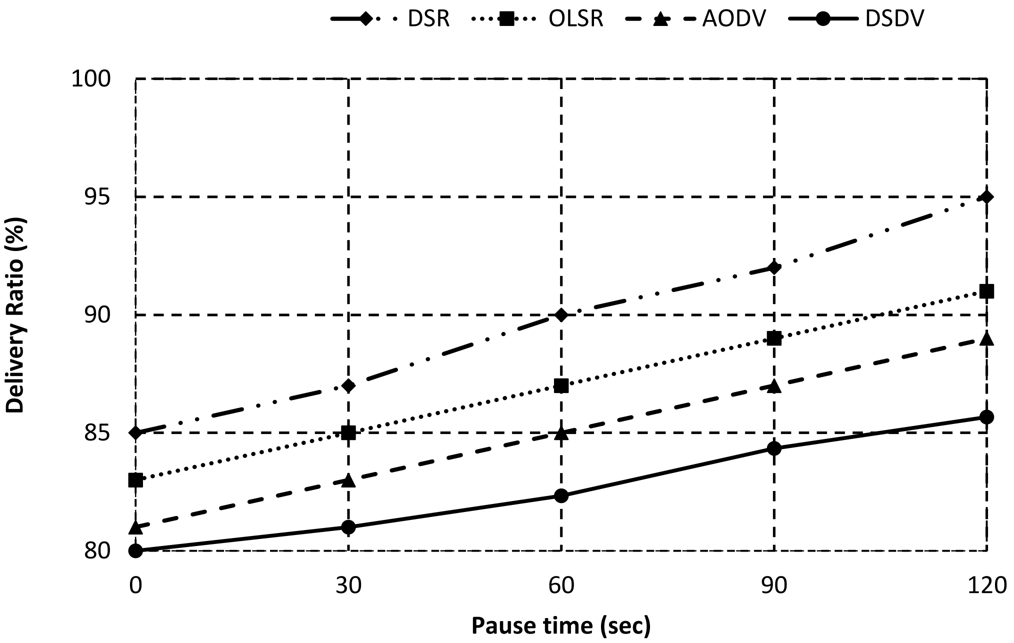
(b) 100 nodes

Figure 4. Throughput for Random Waypoint Model

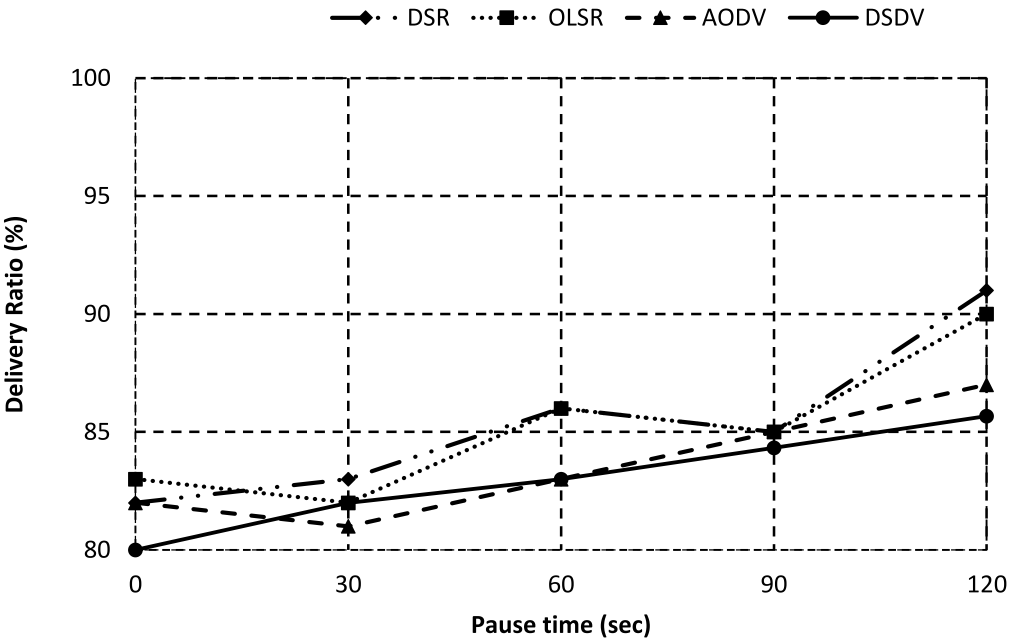
2.4.2.3. Delivery Ratio

The Delivery ratio results are shown in Figure 5 for OLSR, DSDV, AODV and DSR as a function of pause time in the 50-node and 100-node scenarios. The error bars indicate 90% confidence intervals.

We do not count the packets lost due to disconnected destinations as a delivery failure. All four algorithms deliver over 85% packets successfully in the 50-node scenario. The delivery ratio of OLSR and AODV are over 90% in the 50 -node scenario, while DSR delivers almost 92% packets in the 100-node scenario. The delivery ratio of DSR is higher than AODV, OLSR and DSDV in both 50-node and 100-node network topologies.



(a) 50-nodes



(b) 100-nodes

Figure 5. Delivery Ratio for Random Waypoint Model

2.5. Chapter Summary

In this chapter a detailed comparative performance evaluation of reactive and proactive routing protocols which explores the effectiveness of different proactive and reactive routing algorithms in a wide range of ad hoc network simulation scenarios, this which aid the design and the improvement of the of the proposed protocol (LANDY).

The simulation results indicate DSR performing the best in terms of end-to-end delay, but at the cost of low throughput, which becomes more critical with the increase of speed. OLSR, on the other hand, has the best behaviour in terms of packet throughput, but the delay increases dramatically with speed.

OLSR behaves similarly to DSR for the end-to-end delay and to AODV for Packet throughput. As the speed increases, the end-to-end delay tends to increase for all protocols.

This is predictable due to the dynamic changes in the topology of the network. As in the previous case, AODV exhibits the lowest end-to-end delay. The packet throughput for both on-demand routing algorithms has a similar behaviour, with values lower than OLSR and DSDV.

In general, DSR outperforms AODV, DSDV and OLSR in terms of end-to-end delay, but the packet throughput, is in most cases, at least one order of degree lower, making it a very inefficient algorithm when the resources are limited.

However, AODV exhibits a better behaviour in terms of the end-to-end delay. This improved performance is explained by the soft-state updating mechanism employed in AODV, to determine the freshness of the routes. For a maximum speed in the range from 5 to 30 m/sec, both DSR and AODV have better performance in terms of end-to-end delay for the RWpM.

CHAPTER 3. MAC LAYER IMPACTS ON MANET PERFORMANCE

Research on MANET routing protocols have proved that, multiple OSI layer interactions have major impact on the performance of routing protocol. Therefore, it is essential to investigate the characteristics of lower layers, specifically the physical and MAC (Medium access control) layer, before presenting the new position based MANET routing protocols [45].

3.1. Effects of MAC Protocols on MANET Routing Protocols

The MAC layer play a key factor in defining the mechanism of medium access to the shared wireless medium. Therefore, it is responsible for providing the resources to MNs to gain access to the wireless medium effectively, efficiently and collision free.

Generally, MAC protocols have been classified to contention free and contention based scheme. Many recent research and proposed algorithms combine the two schemes in a single MAC solution and hence it is important to define a new classification approach.

MANETs have their unique characteristics and limitations.

Several MAC protocols have been developed for MANETs in recent years. Figure. 6 shows a classification of MAC protocols for MANETs, based on different approaches and schemes. Ad hoc network MAC protocols can be classified into four types:

A. Contention-based protocols
   - Source-triggered: Data packet transmissions are triggered by the sender MN, and it can be either ‘single channel’ or ‘multichannel’. In single channel, a node will be able to use the entire bandwidth if it wins the contention to the channel, while in multichannel, the entire bandwidth is divided into multiple channels.
   - Receiver triggered: The contention resolution protocol triggered by receiver node.

B. Contention-based protocols with reservation mechanisms
   - Synchronous protocols: It is required that all nodes must to be synchronized, and it is challenging to achieve global time synchronization in dynamic environment.
   - Asynchronous protocols: These protocols use distributed time information for effecting reservations.

C. Contention-based protocols with scheduling mechanisms
   - Node scheduling is done in a way that all nodes get equal amount bandwidth.
   - Scheduling-based schemes are implemented for applying priorities between nodes whose packets are queued.

- Battery characteristics were also considered by some scheduling schemes.

D. Other MAC protocols which don’t fall under the above categories.

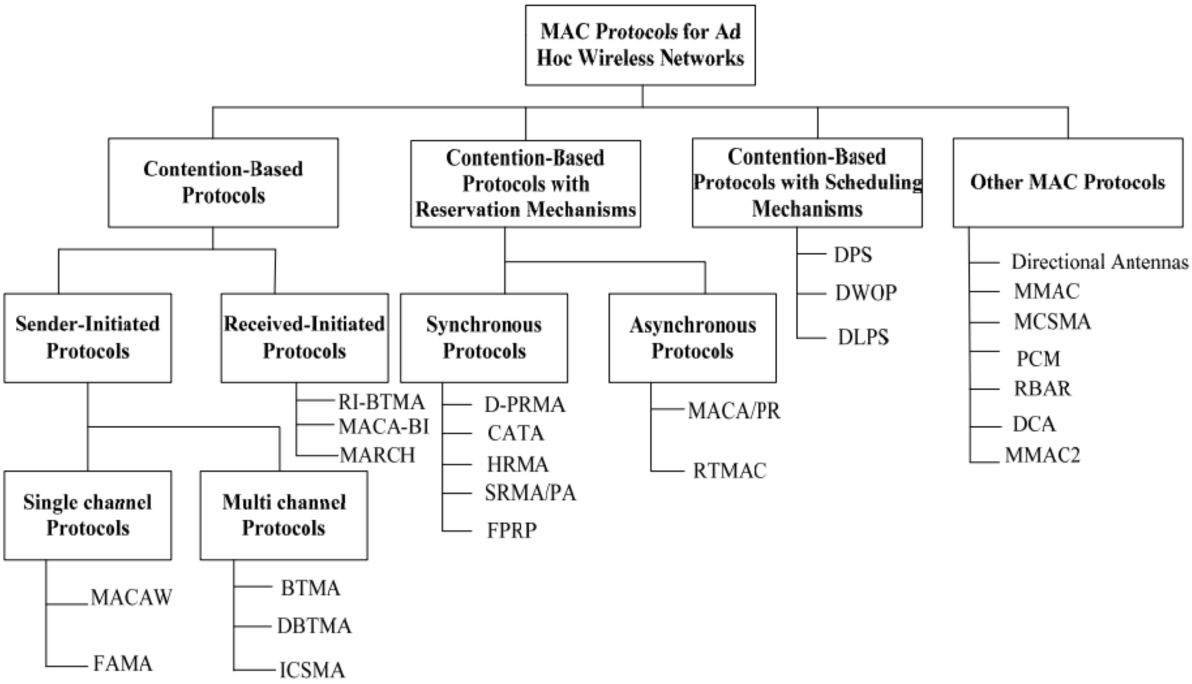


Figure 6. Classifications of MAC protocols

Previous research on MAC protocols which merged the features of both schemes (contention based i.e. Carrier Sense Multiple Access (CSMA) and contention free i.e. Time Division Multiple Access (TDMA) have demonstrated better performance results.

Contention based and contention free approaches have been applied to various parts of some MAC algorithms, which makes the classification and the difference of MAC protocols distorted [46].

For slot allocation in contention free MAC protocol, it uses TDMA because resources are identified first and then get reserved as free to transfer the data, while the resources are estimates in contended based MAC protocols.

The choice of MAC protocol has major impacts on the performance of MANET routing protocols. Table 4 summarises the mechanism of each of major MAC protocols.

Table 4. Summary of MAC Protocols

MAC Protocol	Mechanism
CSMA	CSMA
MACA	PSMA/RTS/CTS
FAMA	CSMA/RTS/CTS
IEEE 802.11 DCF CSMA/CA	CSMA/CA/RTS/CTS/ACK

3.1.1. Carrier Sense Multiple Access

The CSMA listen/ sense to other nodes before initiate the transmission. CSMA is the most common MAC protocols implemented in the MANET research. The term multiple access refers to multiple nodes ‘send and receive’ on the medium, and the broadcast by the source node are received by all other nodes which are connected to the medium [47].

CSMA is a probabilistic MAC protocol in which a node validates the availability of the shared medium before transmitting, such as an electrical bus, or a band of the electromagnetic spectrum. In this CSMA, a node checks the channel for any ongoing transmissions prior sending a packet. If the Channel is free then the nodes start transmission. Otherwise, it sets a random timer if the channel is busy, then tries to transmit the packets after the time expires.

CSMA protocol modification:

- ***CSMA with collision avoidance;*** CSMA/CA collision avoidance is utilised to increase the performance of CSMA by trying to be less "greedy" on the shared medium, which decreases the probability of collisions on the channel. If the node senses the channel is busy prior to transmission, then the transmission is delayed for a "random" interval.
- ***Virtual time CSMA;*** VTCSMA was introduced to evade collision created by nodes transmitting data at the same time. The VTCSMA implement two type of clocks for each individual node, a virtual clock (vc) and a real clock (rc) which sync and provide "real time". If the channel is busy during the discovery/sensing phase, the vc halts and it resets when the channel is available. Therefore, vc tracks faster than rc when the channel is available.

3.1.2. IEEE 802.11 DCF CSMA/CA

The IEEE 802.11 DCF [17] is a standardized MAC protocol for wireless local area networks (WLANs), which uses CSMA and collision avoidance (CSMA/CA) with a binary exponential back-off algorithm.

The IEEE 802.11 MAC protocol defines a Distributed Coordination Function (DCF) [14], which is similar to the previous MAC protocols during the transmission phase (unicast transmission) of RTS/CTS (Request to Send and Clear to Send) message exchange.

The protocol uses a CSMA/CA with RTS/CTS/DATA/ACK four-way handshaking mechanism. During the discovery phase, the protocol sense the channel, before initiating the data transmission. It triggers the transmission of the data packets in case the channel is free for a time duration that equals to DCF inter-frame space (DIFS). Otherwise, it keeps sensing until the channel is free.

IEEE 802.11 MAC protocol improve the communication speed during the discovery phase because of the ACK (Acknowledgement) inclusion, which allows immediate retransmission by confirming that the data packet was successfully acknowledged.

In addition, the inclusion of ACK help to detect the interference by the hidden terminal which was not detectable during the CTS transmission. Each node is required to wait for a random back-off time instead of transmitting straight away, which help to avoid collisions. The back-off time is calculated by the binary exponential back-off algorithm.

If the back-off timer expires for the first transmitter node, it starts transmitting another RTS frame to its target receiver node, which will respond with a CTS frame after a period of short inter-frame space (SIFS). After transmission and ACK of RTS/CTS frames, the neighbouring nodes, within the transmission range of the sender or receiver, should configure their network allocation vectors (NAVs) and halt their back-off timers [48].

3.1.3. Multiple Access with Collision Avoidance

The Multiple Access with Collision Avoidance (MACA) [12] protocol improves upon other protocols in relation to the avoidance of the hidden terminal problem.

The basic idea of MACA is that a wireless network node makes an announcement before it sends the data frame to inform other nodes to keep silent. The hidden terminal issue is illustrated in Figure 7.

Two nodes (A and B) trigger the transmission of the packets to node C at the same time, however, neither node A or B can overhear the transmission of each other. Both nodes send packets to node C at the same time, which result in colliding.

MACA improvement to the avoidance of the hidden terminal problem is by denes the RTS and CTS control packets to announce an upcoming transmission which include the length of the data frame in RTS and CTS [49].

Any node receive the announcement either of RTS or CTS control packets must halt for enough period of time for the data packet to be transmitted. This will help to avoid the collision by the neighbouring nodes during the data transmission.

Figure 8, shows the process of RTS/CTS control messages in simplified environment. When node S transmits the RTS message, both neighbouring nodes (A and B) receive the message and halt their RTS transmission tries.

The same principle applies to node D. If node D responds with a CTS, both nodes (B and C) also receive the CTS and are halt throughout the data transmission. If two nodes send simultaneous RTS frames to the same node, the RTS transmissions collide and are lost. If this happens, the source nodes which transmit the failed RTS packets set a random timer employing the binary exponential backoff algorithm for the next transmission try [50].

WLAN data transmission collisions may still happen, and the MACA for Wireless (MACAW) is introduced to extend the function of MACA. It involves nodes sending acknowledgements after each successful data packet transmission.

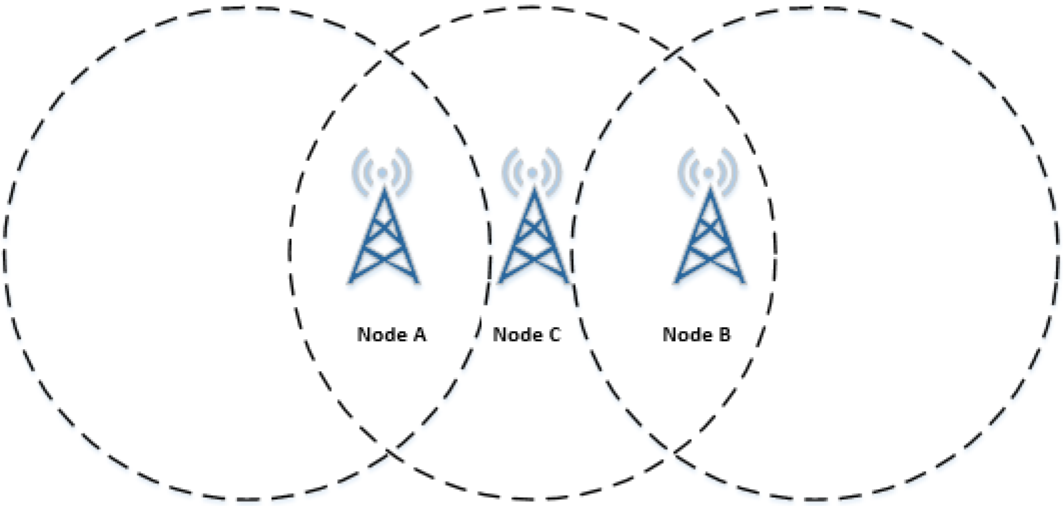


Figure 7. Hidden Terminal Problem

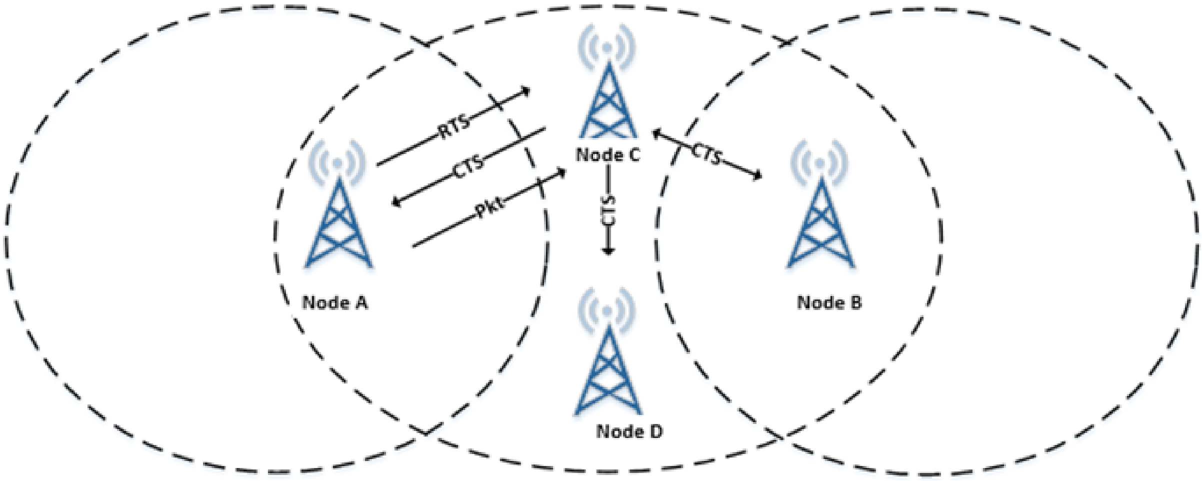


Figure 8. RTS/CTS Mechanism

3.1.4. Floor Acquisition Multiple Access

The Floor Acquisition Multiple Access (FAMA) is evolve from MACA protocol by adding non-persistent carrier sensing to the RTS-CTS exchange phase. FAMA uses random backoff time in case the channel is busy during the listening phase, before sensing the channel again. The implementation of the carrier sense to the control packet exchange helps avoid control packet collisions [51].

3.2. Scheduling Mechanism in MAC Protocols

The dynamic topology and the nature of MANETs poses real challenges in routing and maintaining packets between MNs. The frequent packet transmission, require a scheduling algorithm to control which packet to progress next, so that it improves network performance in high mobility and traffic scenarios.

Scheduling algorithms are major factor to improve quality of service (QoS) in MANET [22]. The priority scheduling algorithm is very common in the recent simulation research on MANET.

In the interface queue, data packets are scheduled in first-in, first-out (FIFO) order and routing packets scheduled in priority algorithm. Network traffic can be categorised into two types: ‘Control packets and Data packets’. Routing protocols in MANET implement various scheduling algorithms.

In all scheduling algorithms, the drop-tail policy is utilised as queue management. Priority is given to control packets instead of data packets, except for the no-priority scheduling algorithm.

Scheduling can be categorised in two types: *1) Packet scheduling and 2) Channel Access Scheduling*.

1) Packet scheduling determining the order in which packets queueing for transmission at any node must be dispatched.
2) Channel access scheduling controls the process on how different nodes share a channel in a conflicted area [23]. Since scheduler controls and arrange the traffic packets. Several scheduling algorithms are discussed below.

3.2.1. No-Priority Scheduling

In non-‘pre-emptive’ scheduling algorithm, service is provided on the basis of FIFO order. Consequently, QoS is not achievable, which is not the case if the traffic is prioritised.

3.2.2. Priority Scheduling

The priority scheduling are used in MANET research to improve performance. It maintains separate destination rapidly, and acquires less queuing in the network. The principle idea of this algorithm is similar to ‘round robin’ technique, where all paths are considered during the transmissions process, and ‘weighted round robin’ scheduler is used to avoid starvation.

Each data packet header carries a complete list of nodes during the transmission process, from the source to the destination. The outstanding hops can be acquired to traverse from the packet headers. In the traditional routing protocols, this information can be acquired from the routing table, which stores the remaining hops to destinations.

3.2.3. Weighted Distance Scheduling

The weighted-distance scheduler is also called a ‘weighted round robin’ scheduler. The process of weighted-distance scheduler is that nodes with shorter distance to the destination, get lower weight to data packets that have longer remaining geographic distances to the destinations. The remaining distance is defined as the distance between a chosen next hop node and a destination node [23].

3.2.4. Round Robin Scheduling

Round robin queue operate per stream queues, and streams are recognised by source and destination pair address. ‘Round robin’ scheduling controls the flow of queue, which send one packet at a time in each path.

3.2.5. Load-Based Queue Scheduling

In load-based queue scheduling algorithm, the scheduling service is divided in two steps: ‘Scheduling policy and Dropping Policy’.

Priorities are assigned to node, based on the level of load, if a node has less load which help in establishing the path to other nodes, this node will get higher priority, otherwise, it avoids the construction of the routes. Node’s load level can be determined by queue length, which is represented by ‘Min or Max’ threshold value. If load is low, the threshold value can be set to Min, otherwise it’s set in to Max.

3.2.6. Cluster-Based Multi-Channel Scheduling

In this type of algorithm, the communication process can be established by two methods; the first method is intra cluster communication and the seconded method is inter c cluster communications. In cluster based communication, the throughput and QoS can be improved by allocating a fixed time slot per packet to each node over multiple channels (i.e TDMA).

In the first method of cluster communication, the packet process of each node within the cluster is managed within its cluster. If the target node is located within the same cluster, the source transmit directly (direct connection), otherwise, it forwards the packet to its own cluster head in order to save battery energy (i.e. uplink).

In the second method of cluster communication, each cluster head transmit frames received from its cluster members to their destination over specific channels. The goal of cluster-based multi-channel scheduling algorithms, is to improve the end-to-end throughput by enhancing the number of TDMA slots in the cluster communications process.

3.2.7. Channel Aware Packet Scheduling

Channel aware packet scheduling algorithm can detect the channel bottleneck and confirm the path life time during the transmission process.

This route lifetime value is utilised as a parameter to represent channel condition from the end-to-end transmission process.

3.3. Simulation Setup and Results

The objective of this simulation is to investigate the impact of MAC layer on the performance of MANET routing protocols. The simulations were implemented using the OPNET network simulator. Node movement is modelled by the RWpM. Nodes move at a speed between 0 and 10m/s. When the node arrives at its randomly chosen destination, it rests for some pause time.

It then chooses a new destination, and begins moving once again. The pause times are varied between 0 and 400 seconds. Each MAC protocol/routing protocol/ pause time combination is run for ten different initial network configurations. Each run is executed for 300 seconds of simulation time and models a network of 100 nodes in a 1500m x 1500m area. Each node has a transmission radius of 300m.

The propagation model is the free space model with threshold cutoff. The radio model also has capture capability, whereby a node may successfully receive a packet even in the presence of noise.

There are 20 data sessions between randomly selected sources and destinations. The bandwidth is 2 Mb/s, the data packet size is 512 bytes, and packets are sent at a rate of four per second by each source. Table 5 shows the parameter values used for the routing protocols in the experiments.

To determine whether the selection of MAC protocols affects the relative performance of the protocols, three results are examined: the number of data packets received by their destinations, the control packet overhead, and the normalized routing load (NRL).

The control packet overhead is computed by counting the number of hop-wise control packet transmissions. The normalized routing load is calculated by taking the total number of per-hop control packet transmissions, and dividing this by the number of data packets successfully delivered to their destinations.

Figure 9, illustrates the number of data packets delivered to destinations in each of the networks. The relative performances of AODV, DSR, and DSDV remains fairly constant while that of OLSR tends to vary by the MAC protocol used. When run over CSMA, OLSR performs best for the higher mobility scenarios; however, while using IEEE 802.11, DSR outperforms the other protocols.

The protocols achieve nearly the same number of delivered data packets, when combined with the MACA and FAMA protocols, with DSR performing slightly better using the FAMA MAC protocol.

Table 5. Parameter Values – MAC Experiments

Parameters	**Value**
Simulation Area	1500 x 1500 sq.meters
Mobility Models Used	RWpM
Pause time	0 – 400 sec
Antenna type	Omni antenna
Traffic model	CBR
Transmitter range	300 m
Routing Protocol	DSR , AODV, DSDV, OLSR
MAC Protocols	CSMA, FAMA, IEEE 802.11 DCF, MACA
Data traffic size	512 bytes
Data packet rate	100 packets/sec
Simulation time	1200 sec
Number of Nodes	100
Node Placement	Random
HELLO Interval	1 sec
Max Allowed Missed HELLO S	4
Update ACK Timeout Interval	1 sec
Retransmission Timer	1 sec
Retransmission Counter	4
Simulation software	OPNET

The protocols have better overall performance using CSMA than using MACA or FAMA because of the RTS/CTS messages. MACA sources transmit RTS packets whenever they have a data packet to send without sensing the channel. This results in an increase in packet collisions and hence decreased throughput.

The collision avoidance mechanism incorporated into IEEE 802.11 for the transmission of RTS packets aids in the reduction of the number of collisions. Consequently, more data packets reach their destinations.

Further analysis of the MAC protocols under UDP can be found in [3]. The number of hop-wise control packet transmissions during each simulation is shown in Figure 10. Because OLSR uses periodic messaging regardless of the underlying MAC protocol, the amount of control overhead generated by this protocol remains relatively constant over the different simulations.

AODV has both triggered and periodic updates, and hence the amount of control overhead increases as mobility increases (i.e., as the pause time becomes shorter). AODV is the only protocol significantly affected by the MAC layer. When run over CSMA, MACA and FAMA, AODV must utilise HELLO messages in order to maintain connectivity. Hence, it is expected that the number of control messages in these simulations is greater than in the IEEE 802.11 simulation.

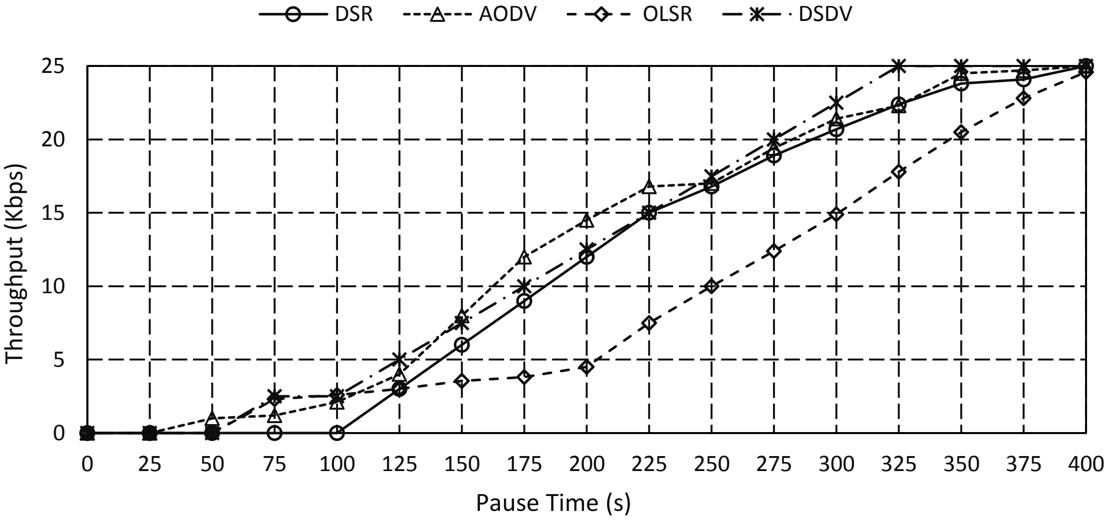
Additionally, the amount of control overhead generated by AODV is directly related to the number of routes it is maintaining. Because there are so many packet collisions when utilising the CSMA MAC layer protocol, AODV is not able to maintain as many routes. Hence the control overhead is lower for this simulation. As the number of routes DSR attempts to maintain increases however, the amount of control traffic generated similarly increases.

The NRL is a measure of a protocol's efficiency. This measure is important because link layer protocols in ad hoc networks are contention-based. This result is shown in Figure 11. DSR consistently has a greater NRL than DSDV, and has greater NRL than AODV in all but a few cases of CSMA.

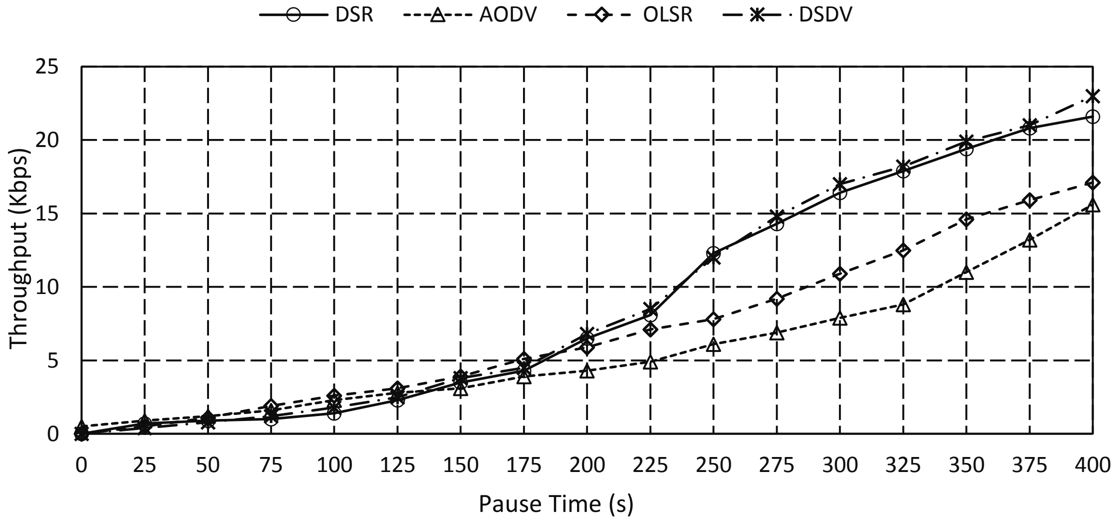
The ratio of control messages generated by OLSR and DSR remains approximately constant, regardless of the underlying MAC protocol. Note the variation in axis scaling.

The NRL quantitative measure varies, because the throughput of DSDV and AODV is dependent upon the MAC protocols used. Hence, this metric aids in the analysis of how efficiently the routing protocols utilise routing packets to deliver data packets.

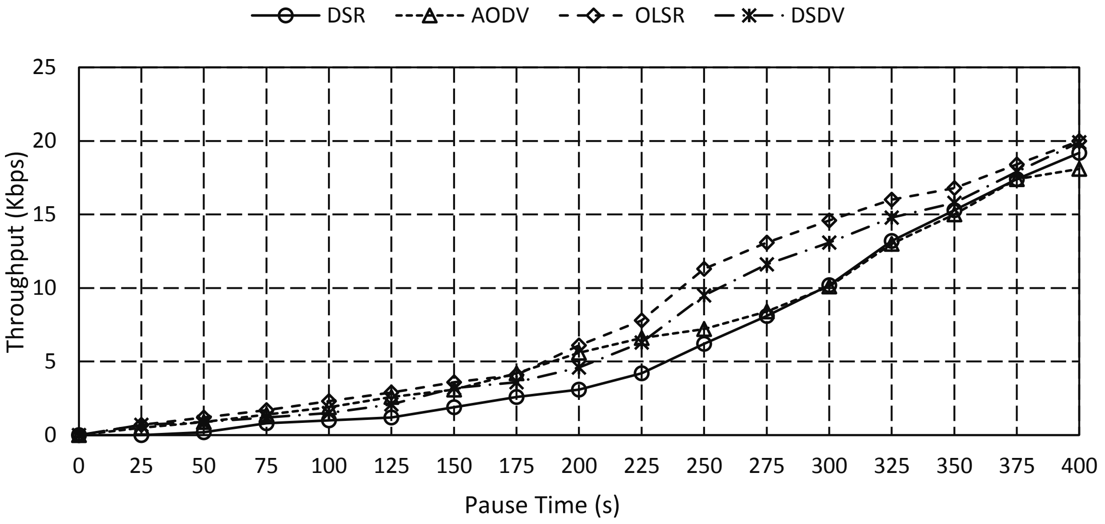
DSR is most efficient when used with IEEE 802.11. This result is expected since DSR does not need HELLO packet transmissions when combined with IEEE 802.11.



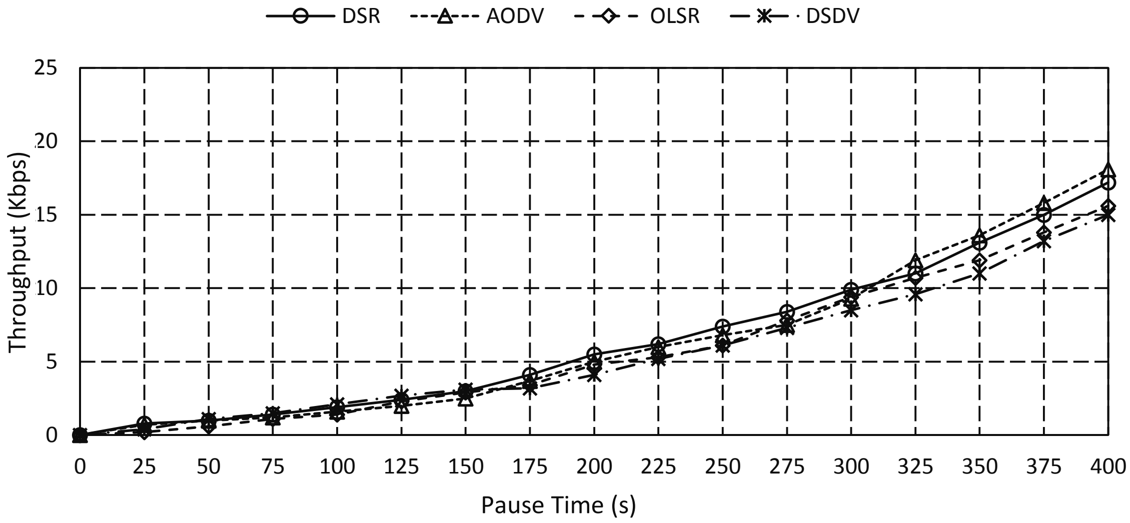
(a) CSMA



(b) MACA

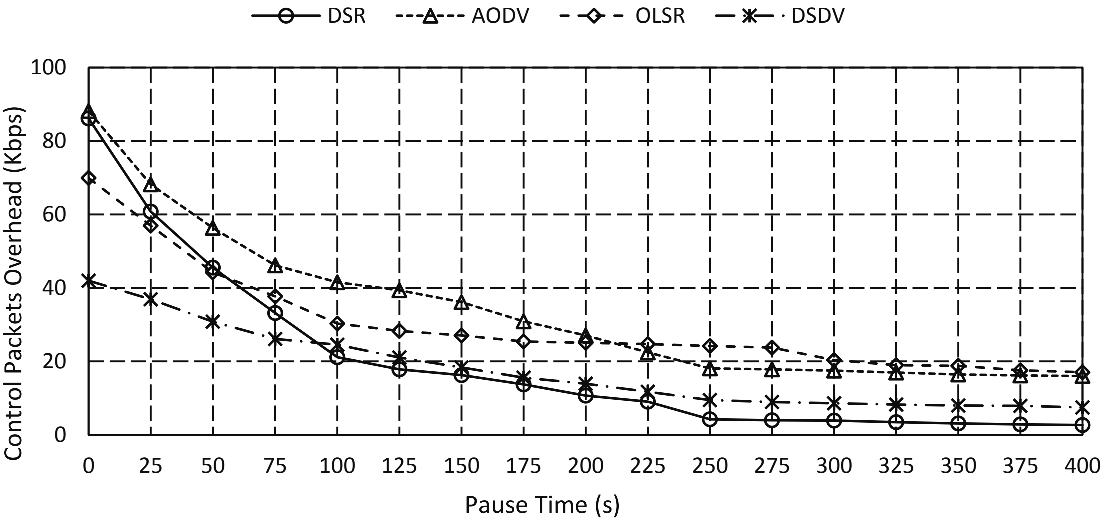


(c) FAMA

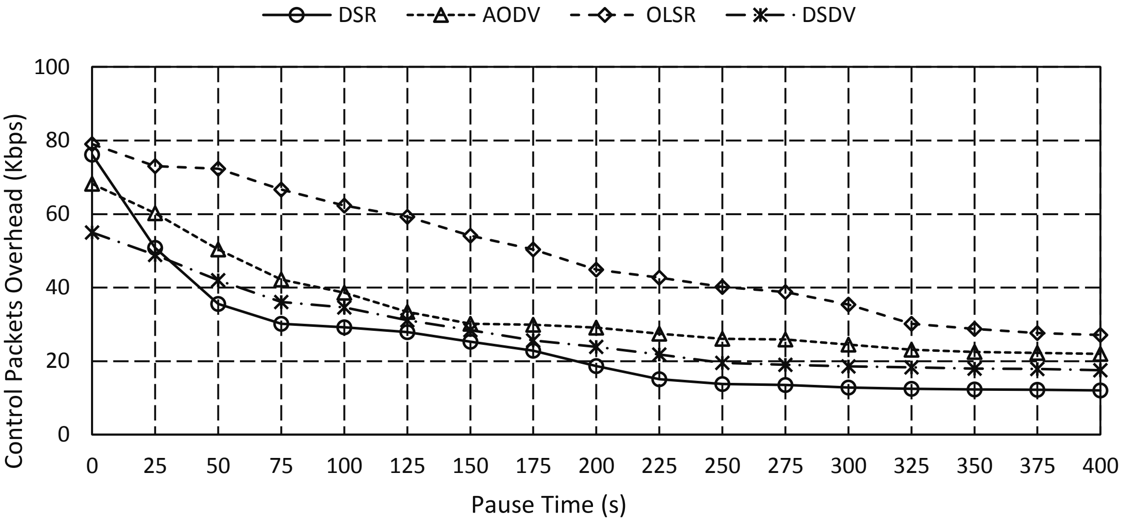


(d) IEEE 802.11 DCF

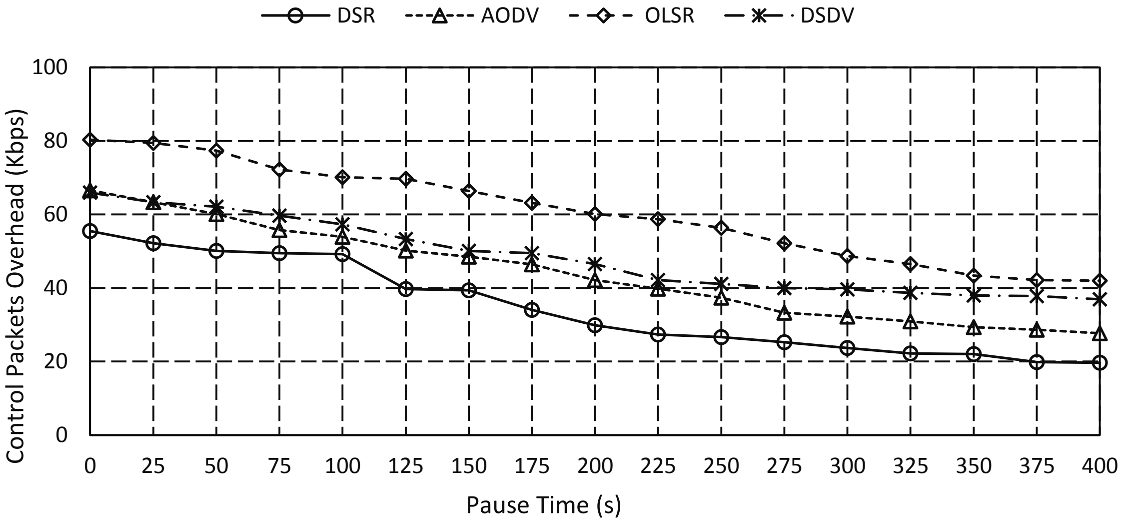
Figure 9. Throughput vs. Pause Time


DSR
AODV
OLSR
DSDV
Control Packets Overhead (Kbps)
0
20
40
60
80
100
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
Pause Time (s)

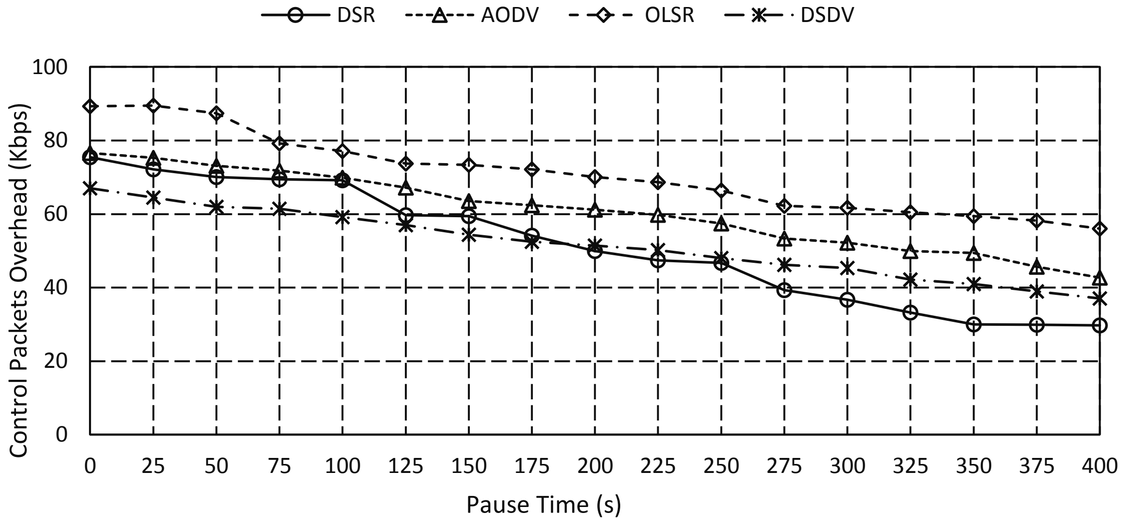
(a) **CMSA**


DSR
AODV
OLSR
DSDV
Control Packets Overhead (Kbps)
0
20
40
60
80
100
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
Pause Time (s)

(b) **MACA**

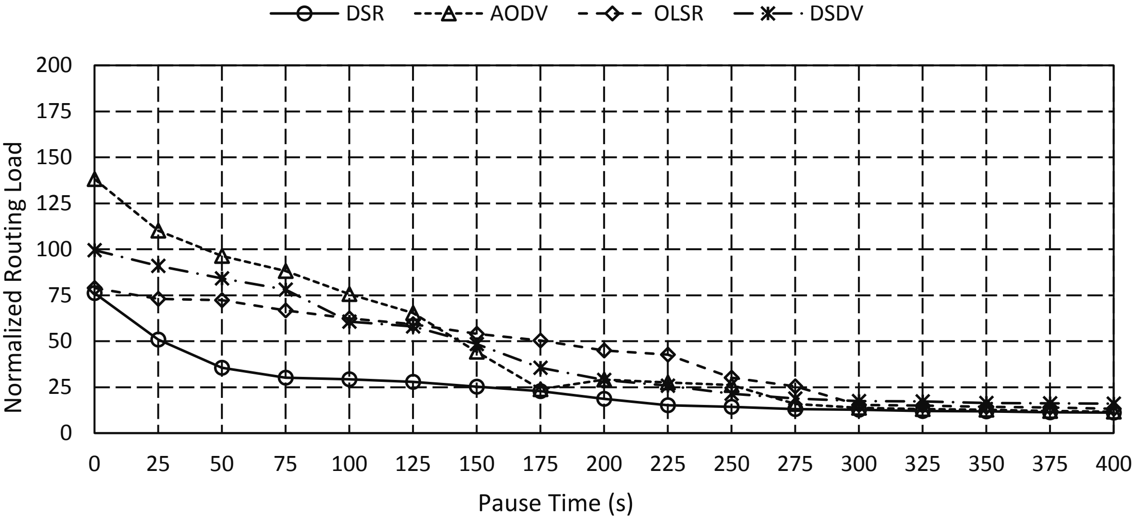


(c) **FAMA**

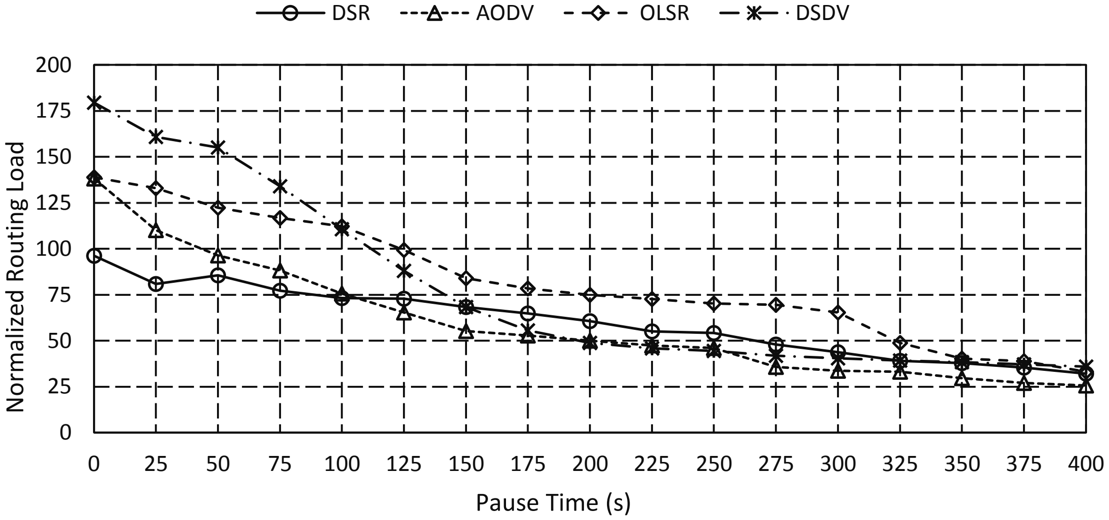


(d) **IEEE 802.11 DCF**

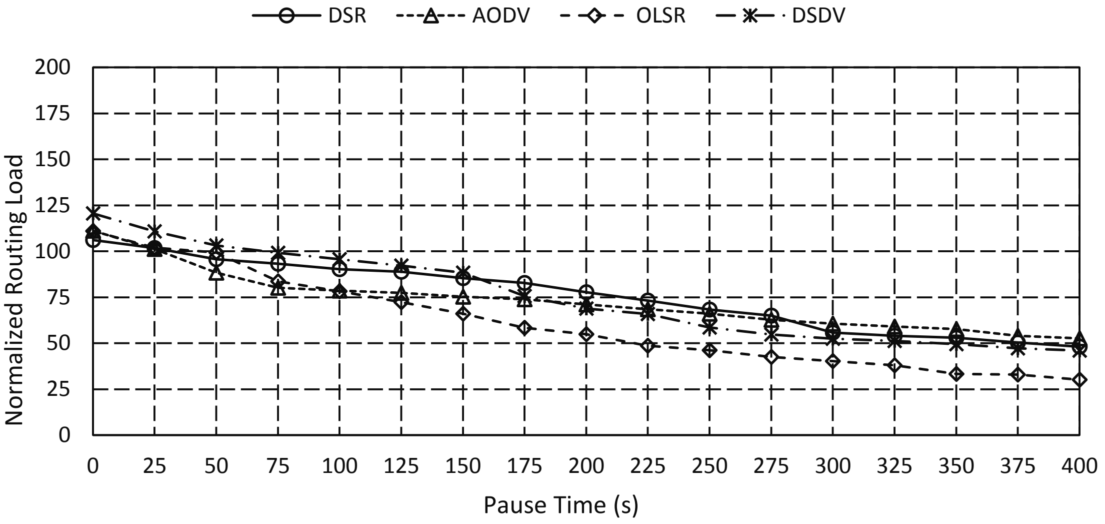
Figure 10. Control Packet Overhead vs. Pause Time


DSR
AODV
OLSR
DSDV
Normalized Routing Load
0
25
50
75
100
125
150
175
200
Pause Time (s)
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400

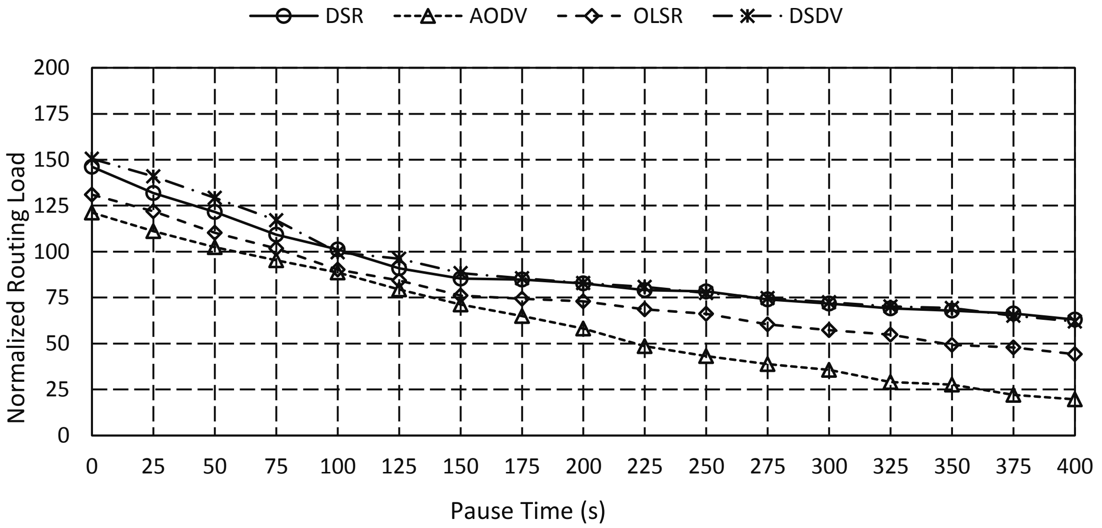
(a) CSMA


DSR
AODV
OLSR
DSDV
Normalized Routing Load
0
25
50
75
100
125
150
175
200
Pause Time (s)
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400

(b) MACA



(c) FAMA



(d) IEEE 802.11 DCF

Figure 11. Normalized Routing Load vs. Pause Time

3.4. Chapter Summary

This section has presented a performance comparison of the DSR, DSDV, OLSR, and AODV routing protocols when combined with varying MAC protocols. The comparative performance of the DSR and OLSR protocols does not show notable difference when run over the different MAC protocols.

Neither routing protocols need operational changes reliant on the underlying MAC protocol. AODV requires periodic HELLO messaging when the next hop is unreachable; the amount of control traffic generated with these MAC protocols is significantly larger than when it is run over IEEE 802.11 DCF.

AODV proves to be sensitive to the functionality of the MAC protocol, and therefore its relative performance differs, depending on which MAC layer is used. The results also show that DSR is most efficient when used with IEEE 802.11 DCF.

This indicates that the reactive routing protocols performance varies, depending upon which MAC protocol is used. The IEEE 802.11 DCF is more efficient than other MAC protocols. The original MAC algorithms for MANETs are typically single-radio per node, operating on a single channel.

Control, data packets, and control messages are essential for coordination of data transfer. As data transmission between all the nodes are broadcast over the same channel, the most widely used and implemented single-radio, single channel MAC protocol for MANETs is the IEEE 802.11DCF.

Much research has been carried out on improving IEEE 802.11 DCF performance by implementing directional antennas. The disadvantage of this technique is, if a node is trying to transmit data, it has to be active node, which means the nodes are receiving data from another node at the same time. Otherwise, the node will be idle, because if there is active transmission in the neighbourhood, then all a node can do is wait for the channel to become idle before it can transmit data.

CHAPTER 4. PHYSICAL LAYER IMPACTS ON MANET PERFORMANCE

It is important to explore the physical layer and the impact on the performance of MANET routing protocols. In most MANET research, simulation are utilised for the evaluation of protocols. Usually, such simulations concentrate on the proposed protocols higher layer, and tend to ignore other layers, mainly the interactions with physical layer.

In this chapter, we present the set of factors at the physical layer that are relevant to the performance evaluations of higher layer protocols, and investigate the physical layer modelling for OPNET simulator. Such factors include signal reception, path loss, fading, and interference. Our Simulation results show that the factors at the physical layer not only impact the performance of the routing protocols, but it can even modify the relative ranking among protocols for the same scenario.

4.1. Effects of Physical Layer Modelling on MANET Routing Protocols

The Open Systems Interconnection model (OSI) is a theoretical model that describes and standardises the core process of a communication system by dividing it into layers. Figure 12 shows the ISO – OSI reference model.

The Physical layer, is layer 1 in the network stack. The functionalities of the physical layer are to define physical and electrical characteristics, provide modulation and coding schemes in the wireless medium [52].

The Data link layer is layer 2, which is divided into two sublayers: Logic Link Control (LLC) and MAC. The LLC sublayer provides interface to the upper layer and error control. The MAC sublayer defines medium access mechanism to the shared wireless medium.

The network layer is layer 3, which provides the functional and procedural means of transferring datagrams from source node, to the target node connected to the network. The physical layer model has a major impact on the performance MANET routing protocols, due to fact that, the wireless channel is subject to noise, multipath fading, interference propagation pathloss, and signal reception.

The majority of MANET routing protocols use simple communication technique by sending periodical HELLO messages (e.g. as specified by RFC 1256 for IEEE 802.11 protocol, with node announcement and gateway to facilitate the path), but efficient protocols should consider realistic physical layers, and accurately gather neighbourhood information, using more advanced techniques than just broadcasting HELLO messages.

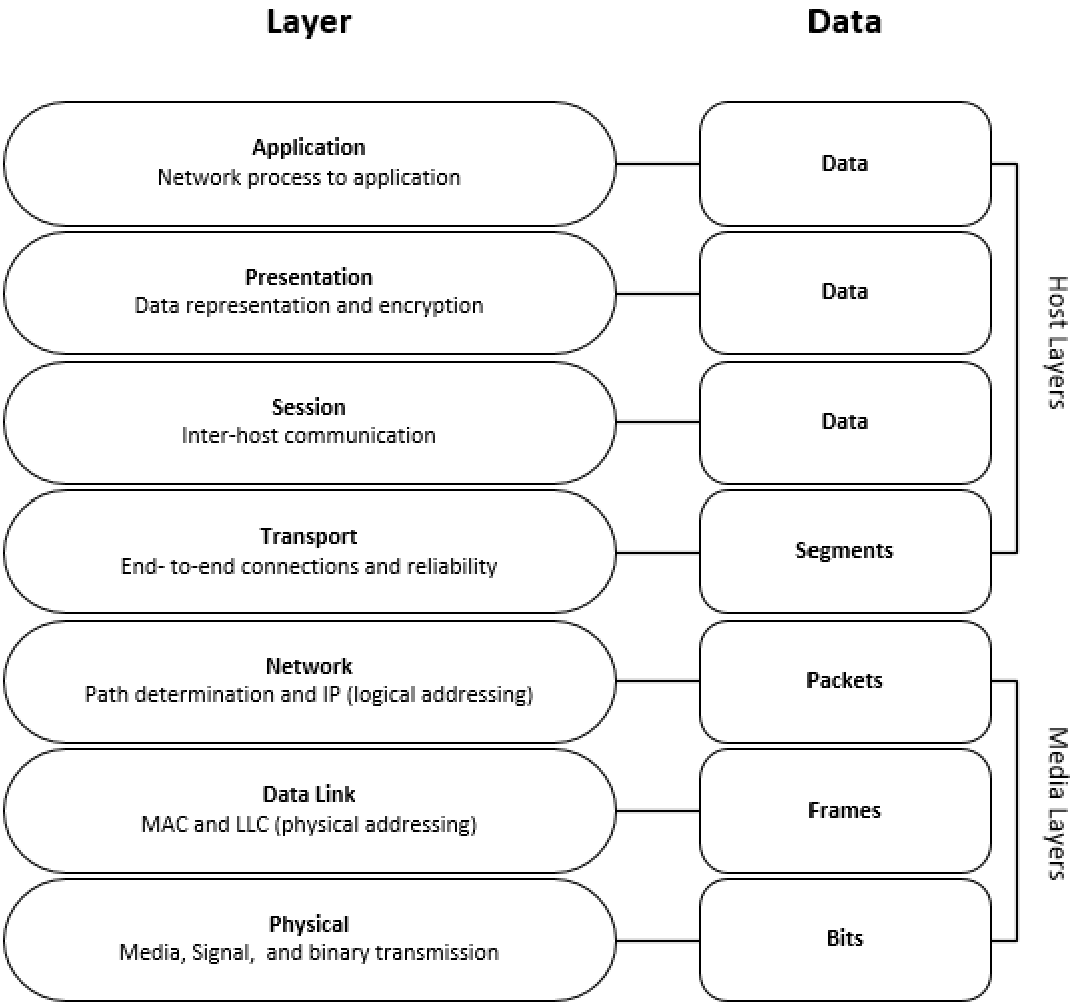


Figure 12. ISO - OSI Reference Model

The most common model in published reports on MANET routing protocols, is unit disk graph. It is very simplistic and idealistic model, where the radio transmission range shapes a perfect circle. Another common model is free space propagation.

It assumes that the transmitter and the receiver have a clear line-of-sight, therefore the received signal strength depends on distance only. Another major model is two-ray ground reflection. This model considers both the direct path, and a ground reflection path between the transmitter and receiver [53].

The two-ray ground reflection model is more precise at long distances than the free-space propagation model, though, in real conditions, the received signal strength is not only reliant on the distance between the transmitter and the receiver, but also on the environment. Additionally, a successful data transmission over a link might not be the same, or guarantee the delivery for the next data packet transmission if the environmental conditions fluctuate.

Another widely used model in MANET research is the approximation function, which is implemented for the evaluation of devices and protocols. Usually, such simulations model emphasis on the particular higher layer protocols that are being proposed, and give less focus at other layers, predominantly the interactions with physical layer models. Although propagation models such as fading, shadowing and path loss are not part of the radio physical models, they regulate the data flow assigned to the physical models, and have huge impact on their performance [54].

4.1.1 Interference and Signal Reception

The range of a radio system is based on the definition of a signal to noise ratio (SNR), and the interference interrupts the packet reception at the physical layer. Computation of interference and noise at each receiver is an important factor, as this process becomes the basis of SINR (Signal to Interference and Noise Ratio). SINR is defined as the power of a certain signal of interest, divided by the sum of the interference power (from all the other interfering signals) and the power of some background noise.

SINR is usually used to measure the quality of wireless connections, taking into the consideration other factors such as the background noise, interfering the strength of other simultaneous transmission. SINR has a resilient link with FER (Frame Error Rate) on the channel in wireless communication modelling. Usually, two common signal reception models are used in MANET simulation: SNR threshold based and BER based models.

The concept of SNR threshold model, is to allow only signals with value above the defined SNR threshold [55].

Where BER model decides probabilistically if the frame received successfully. This is depend on the frame length and the BER gathered by SNR model. SNR can be good in some scenarios as it requires less computational cost, but BER based model is more realistic and precise than the SNR threshold model.

4.1.2 Multipath Fading

Multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths. Fading is a fluctuation of signal power at receivers, triggered by the multipath signal transmission and/or the node mobility that makes different path layout from transmitters.

Most common fading models implemented to describe the MANET environments are Rayleigh and Ricean distributions model.

Rayleigh is used for dense MANET environment with no line of sight conditions between the nodes, whereas the Ricean fading model is used in environments where line of sight path exist between nodes. Another model which is stated to as an idealistic channel condition where no signal fading occurs is called ‘Additive White Gaussian Noise’ [56].

4.1.3 Pathloss

Generally, the degradation in power density of a signal fades with distance, is called a path loss. Path loss is a key factor in the analysis and design of the link in MANET. Path loss may occur as result of many factors, for example free-space loss, refraction, diffraction, reflection, aperture-medium coupling loss, and absorption.

Path loss is also impacted by transmitter and the receiver distance, environment layout, location/type/height of antennas, and propagation medium. One of the major models used in MANET simulation is the two-ray path loss model. Which is suitable for line of sight environments.

Another model is the ‘free space model’. It is utilised in MANET as a basic reference, and perfect propagation model. Due to nodes far from the source, it can receive packets, which often result in less hops reaching the target destination node.

Therefore, simulation results, with the implementation of this model, might have some improvement in comparison to other path loss models, but it is not the case in some scenarios, the signal propagation with little power loss may generate stronger interference for concurrent transmissions [57].

4.1.4 OPNET Physical Modelling

OPNET is a commercial tool from OPNET Technologies Inc. [17] for modelling and simulation of communications networks, devices, and protocols. It has been developed since 1986, and is widely recognised to be the state-of-the-art in network simulation.

It is really important to investigate the physical layer modelling for OPNET simulator, since we are using the tool to simulate MANET routing protocols [58].

OPNET uses free space pathloss model without fading model. OPNET defines the signal reception level by BER based model or SNR, if the threshold value is specified. The software comprises several tools and is divided in several parts:

- OPNET Modeler
- OPNET Planner

- Model Library
- Analysis tool

Features contained within OPNET are: An event-driven scheduled simulation kernel and integrated analysis tools. Table 6 shows characteristics and common implementation of MANET simulation environments. OPNET internal architecture is organised in a hierarchical structure. The lowest level is customisable.

Process models are designed as finite state machines. State and transitions can be graphically specified using STD (state-transition diagrams), and the status of each state is programmed with Proto-C.

Table 6. Characteristics and Common Implementation of MANET Simulation Environments

Characteristics' of Simulation	Possible alternatives and implementations
Supported simulation types	Discrete-event, trace-driven, Monte Carlo
Topologies	Flat, Random, Hierarchical, Position based
Definition of topologies	Script languages, Data files, Graphical interfaces
Data traffic generation	Sampling from probabilistic distribution, Real data
Traffic profiling	Online data collection and statistical analysis tool
Monitoring support	Graphical interfaces, trace generation
Modules for the OSI layers	Routing algorithms, MAC, Physical and link layers
Mobility models	Gauss-markov, Random walk, Random waypoint
Models for radio propagation	Open space with ground reflection, shadowing effects
Modifiability and extensibility	Open and modular software design
Scaling	Efficient management of memory and CPU resources
Ease of Use	Programming tools, graphic interface, documentation
Scientific acceptance	Number of publications using the simulator
Type of software license	Commercial, public domain
Computational platforms	Windows, Linux, Parallel, and distributed systems

Process models are then configured with menus, and organised into data flow diagrams that represent nodes by using the graphical node editor. Utilising the graphical network editor, nodes and links are selected to build up the topology of a network. The analysis tool offers a graphical interface to view and change the data gathered throughout the simulation runs, and results can be analysed for any network element.

For performance evaluation from application layer perspective, OPNET Planner is used to allow administrators to evaluate the performance of the simulation scenarios, without programming or compiling.

Models such as ‘planner analyses’ and ‘performance by discrete-event simulations’ are built using a graphical interface. Also, new models can be defined. Therefore, he has the option to choose pre-defined models (from the physical layer to the application) from the library and set attributes or define a new model (MIL3's modelling service).

The wireless module of OPNET comes with the essential modules in terms of mobility and radio propagation models, as well as in terms of full protocol stack. An over-all summary of OPNET's features: OPNET is a well-established and highly professional product [59].

4.2. Simulation Setup and Results

The Objective of this simulation is to investigate the impact of Physical layer on the performance of MANET routing protocols. Two studies were conducted using the OPNET network simulator. Table 7 shows the parameter values used in the experiments. The purpose of the first scenario, is to assess how the data load impacts the routing protocol performances, in two physical layers environments. In this study, AODV, DSR, DSDV, and OLSR are used as the routing protocols with default settings. In this scenario, all the nodes can randomly send data to any destination within the network.

Each scenario run is executed for 1200 seconds of simulation time and models a network of 100 nodes in a 1500m x 1500m area. The radio transmission range is set to 300m in order to avoid the networks partition.

The radio transmission pipeline is based on a free space model. The second scenario has the same number of nodes and two different mobility models ‘GMM, and PRGM”. The nodes speed is varying between 0 and 30 m/sec.

In this scenario, AODV, DSR, DSDV, and OLSR are used as the routing protocol with default settings. All protocols used in the two simulations (e.g. MAC, IEEE 802.11) are the same. In both scenarios, a fixed mobile transmitter sent a 512 bytes data packets to a specific MN each second. Each routing protocol is run for ten different initial network configurations.

Table 7. Parameter Values – Physical Layer Experiments

Parameters	**Value**
Simulation Area	1500 x 1500 sq.meters
Mobility Models Used	RWpM
Antenna type	Omni antenna
Traffic model	CBR
Transmitter range	300 m
Routing Protocol	DSR , AODV, DSDV, OLSR
MAC Protocols	IEEE 802.11 DCF
Data traffic size	512 bytes
Data packet rate	100 packets/sec
Simulation time	1200 sec
Number of Nodes	100
Node Placement	Random
HELLO Interval	1 sec
Max Allowed Missed HELLO S	4
Update ACK Timeout Interval	1 sec
Retransmission Timer	1 sec
Retransmission Counter	4
Simulation software	OPNET

The results are shown on Figure 13. In all scenarios, the results obtained from the two power models are very different. The constant line is for the OPNET original power model, and the dotted one represents the power model with path-loss.

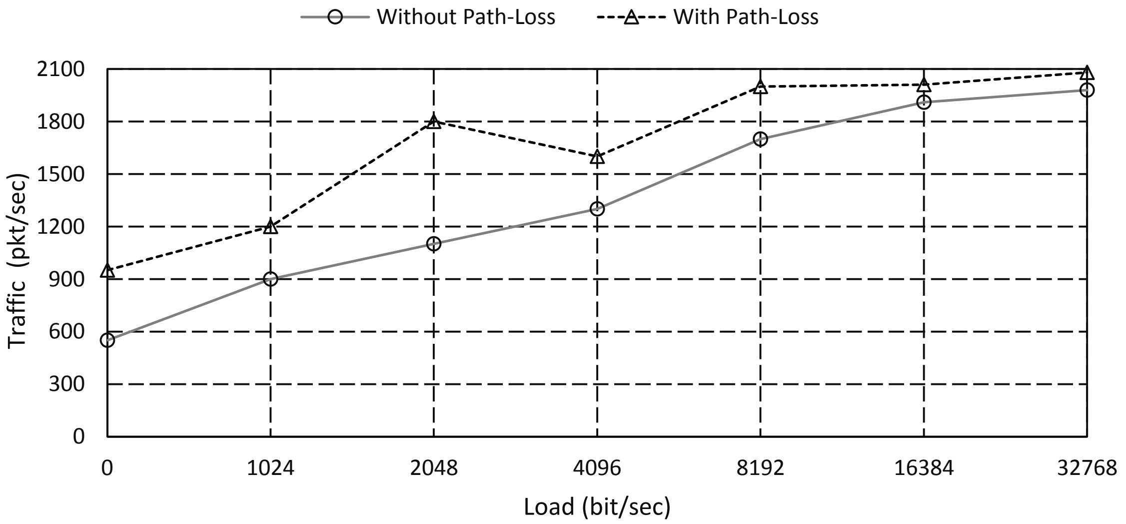
We noticed the results are quite similar when the nodes are close to each other, but after 20sec of simulation, as the node move away from each other, the number of hops between the transmitter and the receiver increase. During this time, the traffic received by the nodes acquired from models with pathloss and fading fluctuates from the default OPNET model. Due to the power model, more accurate definition of the real state of the environment which impacts the values of the signal for the target node.

Therefore, real performances of AODV, OLSR, and DSR can be more efficiently analysed. AODV perform better than DSR, DSDV, and OLSR. Due to AODV are able to choose a more reliable route with the OPNET propagation model.

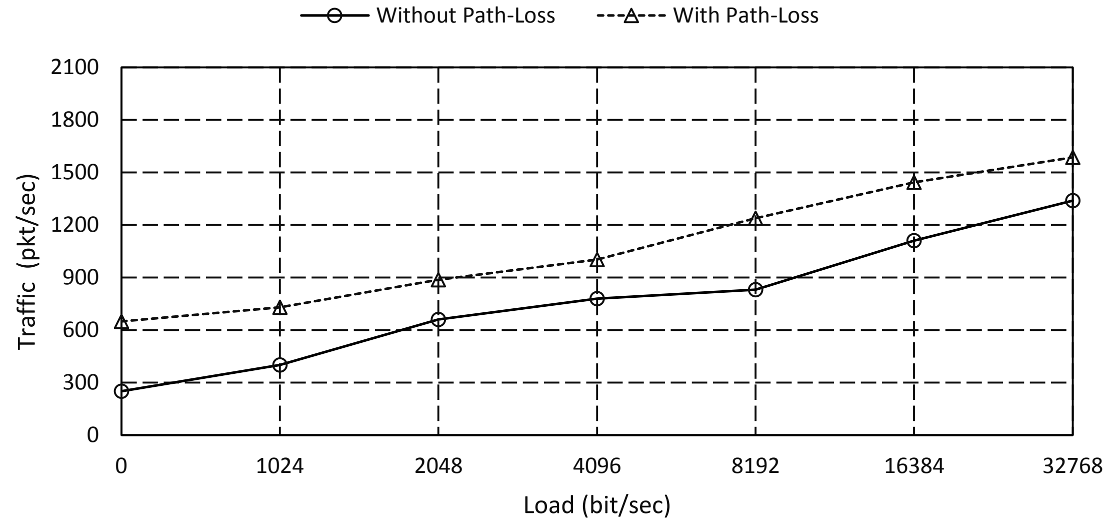
Hence, the number of route errors is much smaller under both models, compared to other routing protocols. Also, we noticed excessive difference in the two scenarios when the network load increases, due to the overhead generated by the protocols. AODV routing algorithm does not produce large amount of overhead comparing to the other protocols, as the network area is small in this particular case.

Moreover, we observed the computational overhead is high, when considering a MAC layer, especially in high node density scenarios, as the amount of events and states increase throughout the simulation run.

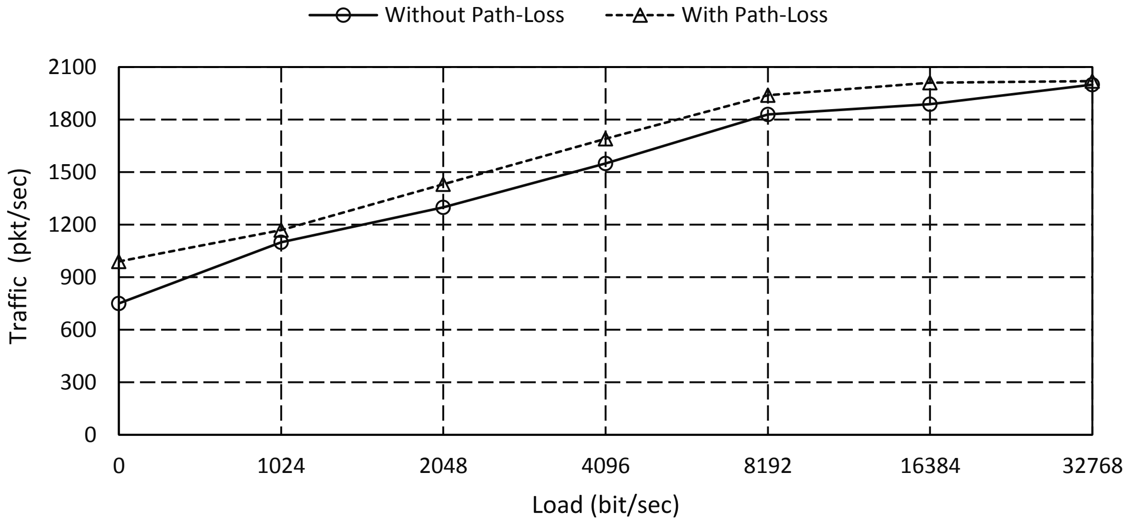
Overall performance of AODV remains high, and marginally decreases when implementing more accurate models. As the medium access control layer decreases the amount of collisions and interferers, the overhead needed for computing the SINR is also decreased. The additional overhead created by the MAC layer is hence balanced by the complexity decrease of the physical layer simulation.



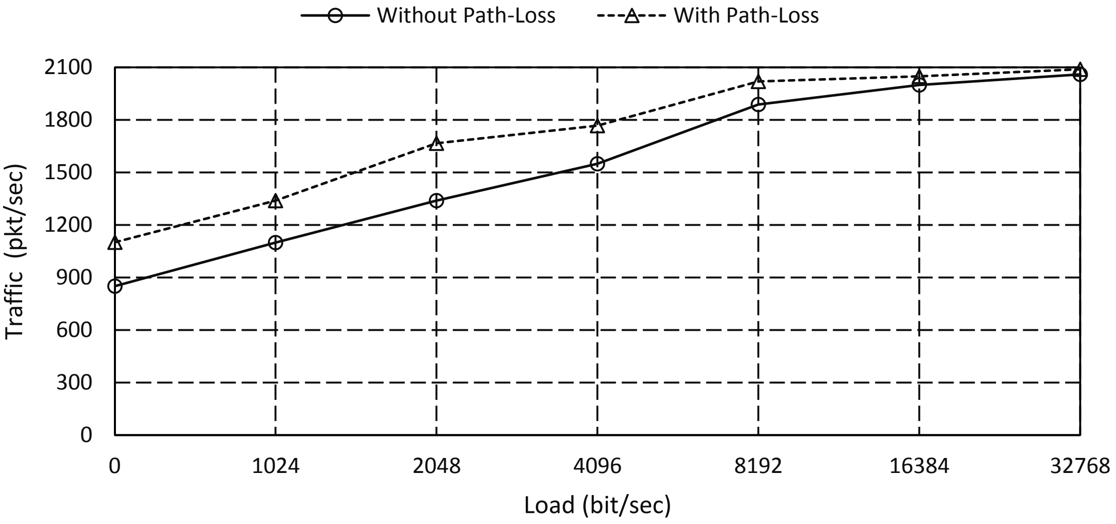
(a) DSR


Without Path-Loss
With Path-Loss
Traffic (pkt/sec)
2100
1800
1500
1200
900
600
300
0
0
1024
2048
4096
8192
16384
32768
Load (bit/sec)

(b) AODV


Without Path-Loss
With Path-Loss
Traffic (pkt/sec)
2100
1800
1500
1200
900
600
300
0
0
1024
2048
4096
8192
16384
32768
Load (bit/sec)

(c) **OLSR**



(d) DSDV

Figure 13. Traffic vs. Load – MANET Routing Protocols

The results of the average RREQ packet sent by each source MNs are shown in Figure 14 and 15 for AODV, DSDV, DSR, and OLSR as a function of radio range in the 100-node scenarios, respectively. The source MNs send RREQ at route discovery and recovery process of route failure on both routing protocols.

Results indicate that, the higher mobility of MNs result in increasing the production of RREQ in the network, which causes routing overhead. With speed increasing more overhead is generating in all protocols. But AODV and DSDV have less overhead than OLSR, DSR. Also, observation of more simulation experiments, shows that more than 60% of routing packets in the network is created by the RREQ packet of MNs.

In general, the performance of OLSR and DSR drops with increasing number of nodes set with low transmission range, but AODV and DSDV perform well, comparing to OLSR and DSR.

Although, both noise calculation and longer physical layer preamble decrease the RREQ, values in all the scenarios, by comparing Figure 14 -a, b, c, and d their impacts on the RREQ performance degradation are quite different.

Due to the IEEE 802.11 MAC re-transmission restrictions, the consideration of interference and noise massively increases the data packet drops, as the accumulated power of interference signals and noise can rise the chances of frame drops, including MAC control frames. This will leads to reduction in the overall traffic.

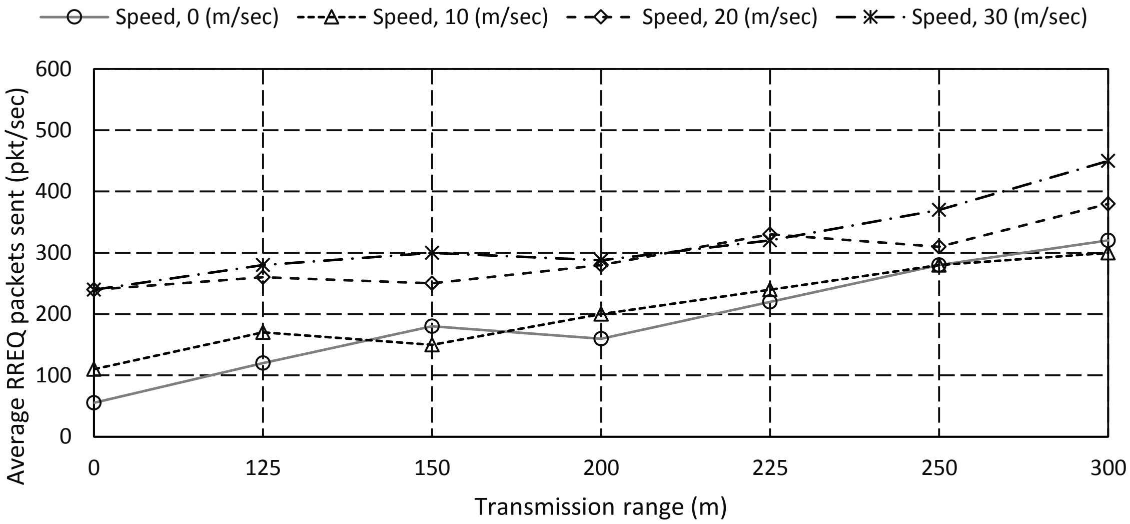
The dropped data packets are not forwarded further to the targets nodes, and the increase in the packet drops at the MAC layer decreases the overall traffic, resulting in the decrease in the packet drops due to the outgoing queue overflow.

Results also show that the impact of RPGM Figure 15 on routing performance is minimal, compared with GMM. Such performance is due to MNs closeness, which restricts movement to within a small area around the reference point.

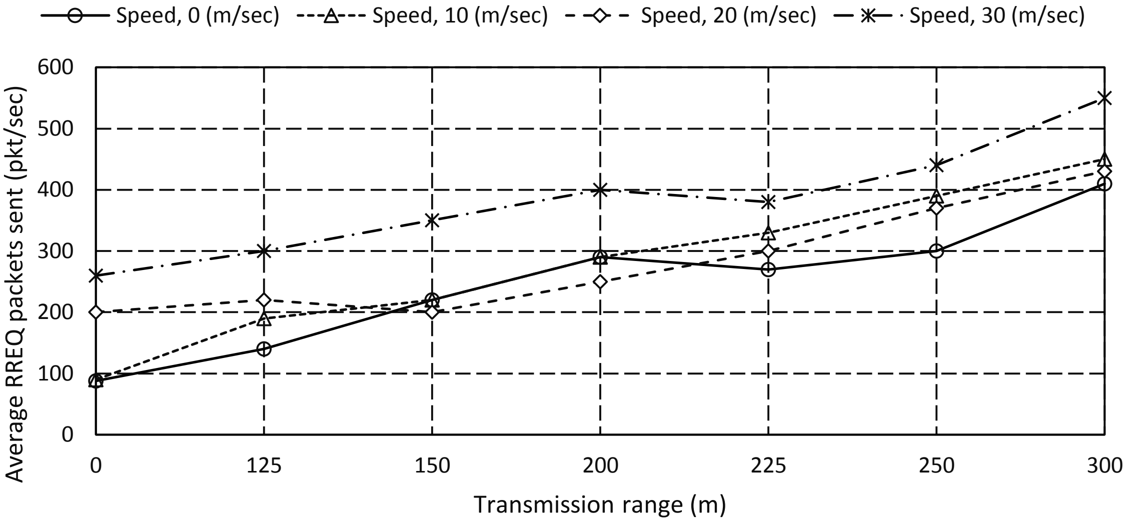
As a result, link connectivity increases, leading to less unidirectional links occurrences. On the other hand, MNs in GMM are uniformly distributed.

Consequently, nodes are more vulnerable to form unidirectional links. In addition, results show with the speed increasing, each metric is getting worse in some way. These results exist, since the topology of the network is more unstable with the speed increasing.

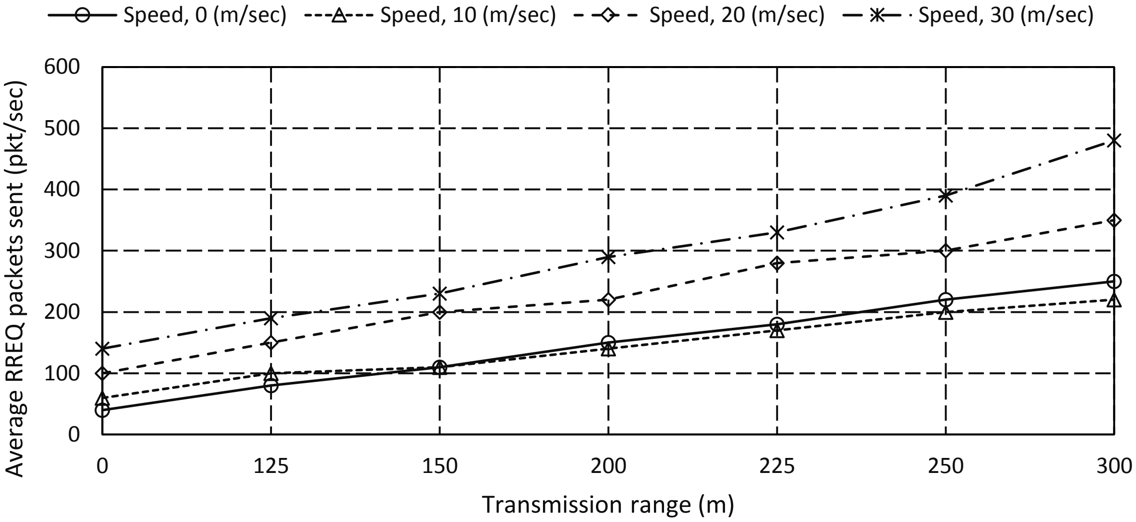
As a result of the RPGM model only has pause time in simulation boundary, and the MNs need to keep moving in the same direction until they reach the border of the simulation area. The metric in the RPGM model, is better than that of the GMM model.



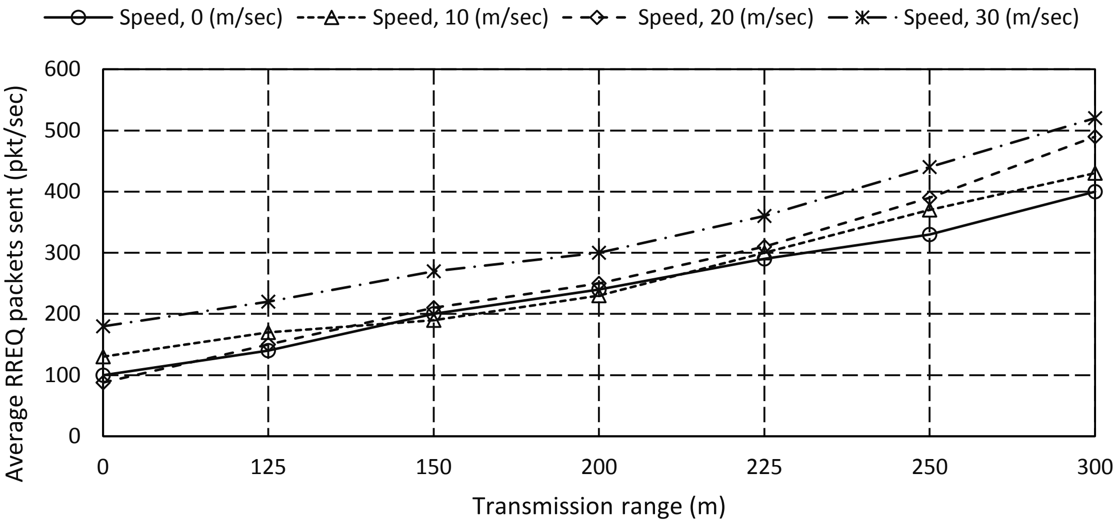
(a) DSR


Speed, 0 (m/sec)
Speed, 10 (m/sec)
Speed, 20 (m/sec)
Speed, 30 (m/sec)
Average RREQ packets sent (pkt/sec)
600
500
400
300
200
100
0
0
125
150
200
225
250
300
Transmission range (m)

(b) AODV

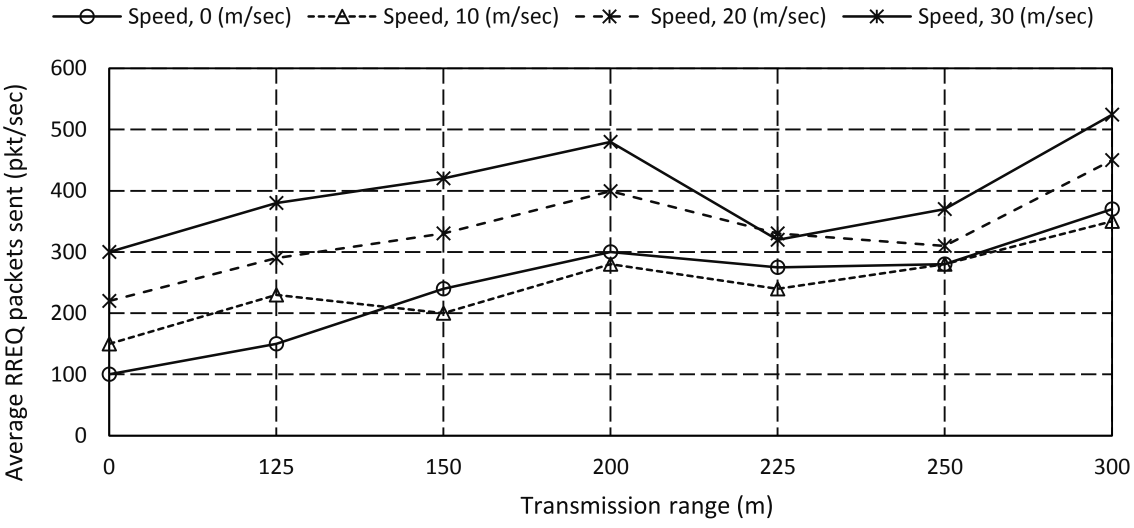

Speed, 0 (m/sec)
Speed, 10 (m/sec)
Speed, 20 (m/sec)
Speed, 30 (m/sec)
Average RREQ packets sent (pkt/sec)
600
500
400
300
200
100
0
0
125
150
200
225
250
300
Transmission range (m)

(c) OLSR

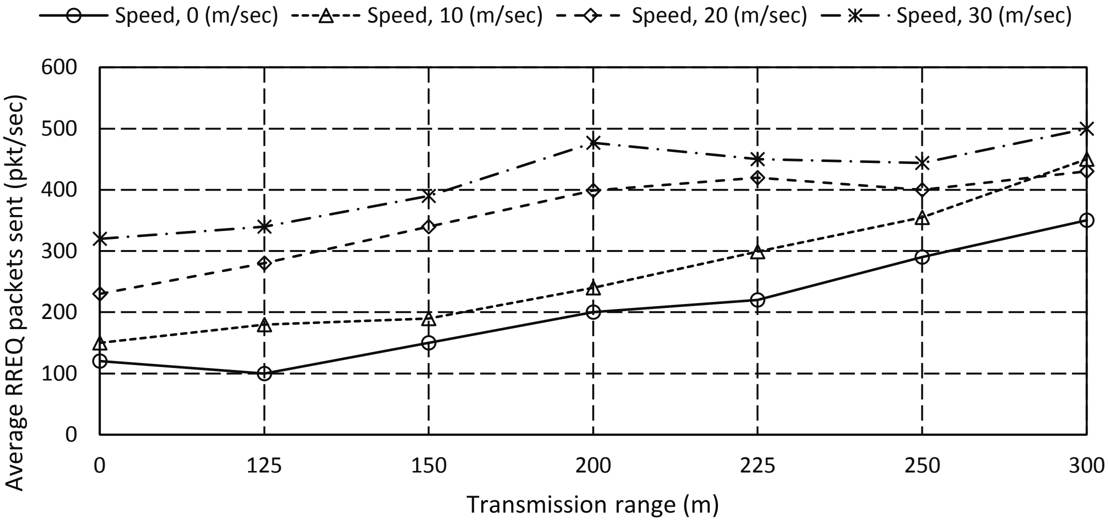


(d) DSDV

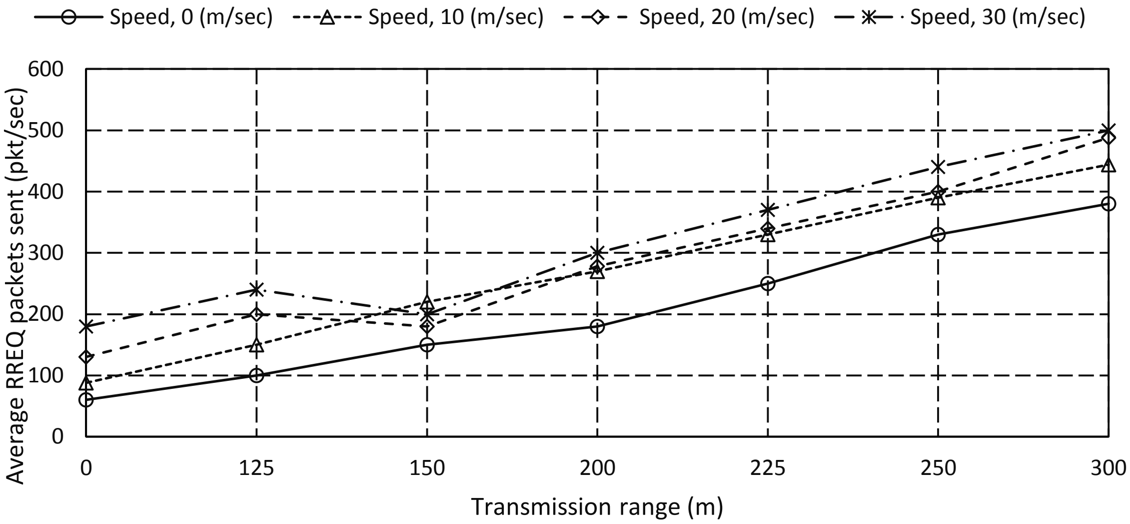
Figure 14. Average RREQ Packet Sent vs. Radio range – GMM



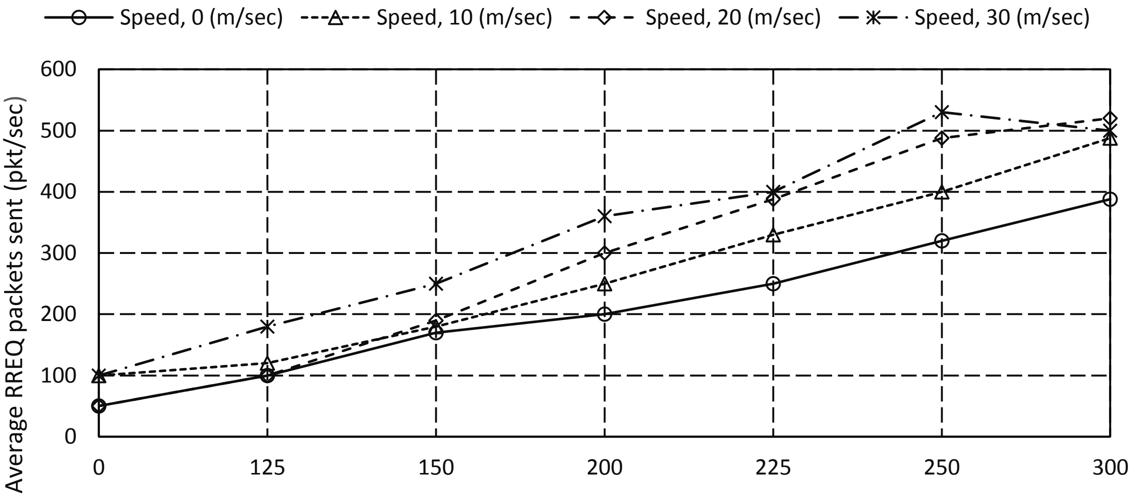
(a) DSR


Speed, 0 (m/sec)
Speed, 10 (m/sec)
Speed, 20 (m/sec)
Speed, 30 (m/sec)
Average RREQ packets sent (pkt/sec)
600
500
400
300
200
100
0
0
125
150
200
225
250
300
Transmission range (m)

(b) AODV


Speed, 0 (m/sec)
Speed, 10 (m/sec)
Speed, 20 (m/sec)
Speed, 30 (m/sec)
Average RREQ packets sent (pkt/sec)
600
500
400
300
200
100
0
0
125
150
200
225
250
300
Transmission range (m)

(c) OLSR



(d) DSDV

Figure 15. Average RREQ Packet Sent vs. Radio range – RPGM

4.3. Chapter Summary

Our study results indicate that the factors at the physical layer, not only impact the performance of the routing protocol, but it can even change the relative ranking between routing protocols for the same environment. Radio propagation models used in MANET simulation, are limited to fading, path loss and shadowing.

Fading is a difference of signal power at receivers produced by the node mobility or, environmental fluctuations that generate variable propagation conditions from transmitters. Another important model for signal propagation is the path loss, which defines the average signal power loss along a given path on a particular environment. The two-ray path-loss model is suitable for line of sight environments, where reflections against scatters are significant.

In a free-space model, even nodes far from the transmitter can receive packets, which may result in less hops to reach the target node in MANETs.

Furthermore, since there is a big difference (outlined) in both scenarios with the default model, more experiments with others major routing protocols ‘reactive or proactive’ need to be carried out.

It is essential to develop new statistics for better routing protocols performance evaluation of other physical layer factors.

CHAPTER 5. NODE MOBILITY AND MOBILITY MODELS IMPACTS ON MANET PERFORMANCE

MANET is one of the potential technologies that can support advanced packet services and real-time applications, which also become one of the most innovative and challenging areas of wireless networking. It is accepted by IETF, that routing strategy is a most important research problem. In order to evaluate routing protocol performance in MANET, the protocol should be tested under realistic conditions (real time) such as arbitrary obstacles, a sensible transmission range, limited buffer space for the storage of messages, representative data traffic models and realistic movements of the MNs (i.e. a mobility model).

The main characteristics of MANETs, are a lack of a fixed infrastructure, very limited bandwidth and mobility of all the nodes. These have posed additional challenges in the design and implementation of protocols to support these networks [60].

The potential for a rapidly changing topology imposes new requirements for routing protocols to maintain routes through the network, without degrading the overall performance by excessively flooding the network with link state advertisements or routing table updates. To satisfy these requirements, the research community has devoted a tremendous effort, resulting in the development of several routing protocols during the last few years [4, 6, 18, 19, 24].

However, in the implementation of MANET routing protocols, the design process has to be accompanied by performance evaluation and testing of the new routing strategies.

Simulation plays a key role in developing and testing new MANET routing protocols. Different theoretical MMs have been developed to represent the mobility patterns of nodes under different circumstances.

However, in some cases the simulation tools only support a very limited number of these models. For scenarios important to applications such as FCS, these methods may not accurately reflect how the network will be used [61].

It is important to evaluate and compare the performance of different MANET routing protocols applied to FCS scenarios and incorporate more advanced mobility models.

It is necessary to choose the appropriate mobility model for each scenario, and to recognise the impact of the model on the performance of the routing protocol by relating the results to key performance parameters, as defined by [33].

It is desirable for a MANET routing protocol to include the following characteristics:

- Distributed: MANET routing protocol requires to execute its process in a distributed manner, due to the decentralized nature of its network.

- On Demand Operation: It is important to utilise the resources more efficiently (power and bandwidth), because traffic distribution cannot be assumed.
- Loop Free: Loop free routing, will ensure efficient network operation and better message delivery.
- Security and Reliability: As well as the usual vulnerabilities of wireless connection, an ad hoc network has its specific security problem issues, due to the broadcast nature of wireless transmission.
- Join/Disjoin Nodes: Nodes joining and leaving the network, require an adaptive routing protocol without the need to restructure the complete network.
- Bidirectional/Unidirectional Links: Routing protocol should support bi-directional path, due to the dynamic nature of MANET.

5.1. Mobility Models in MANET

MMs is the foundation of simulation study on various MANET routing protocols. Extensive research has been done into modelling mobility for MANETs, and many MMs have been proposed in the literature [4, 7, 9 15, 22, 30]. MMs designed to represent the motion of MNs, and how their location, velocity and acceleration changes over time.

MMs are used to evaluate the performance of ad hoc network protocols. Since the performance of protocols depends on the mobility model, it is important to choose a suitable model for the evaluated protocol.

Various MMs have been proposed so far, but the most common ones are Random Walk Model, Random Waypoint Model, Probabilistic Version of the Random Walk Model, Manhattan, Reference Point Group Model and Gauss-Markov MMs [12, 24, 27, 31].

A new routing protocol for an ad hoc network should be thoroughly simulated, so it is essential to use a mobility model that accurately represents the MNs that will eventually utilise the given protocol. This will determine whether the proposed protocol will be useful when implemented.

Generally, there are two types of MMs used in the simulation of wireless networks: Traces and Synthetic Models [28, 33]. Traces are those mobility patterns that are observed in real life systems. Trace analysis provides invaluable insights into actual network user behaviour and mobility patterns.

Traces provide accurate information, especially when they involve a large number of participants and an appropriately long observation period [62].

Synthetic models attempt to realistically represent the behaviours of MNs without the use of traces [32, 38]. A mobility model should attempt to replicate the movements of real MNs. Changes in speed, and direction must occur, and must occur in reasonable time slots.

For example, it is not desirable for MNs to travel in straight lines at constant speeds throughout the course of the entire simulation, because real MNs would not travel in such a restricted manner. MMs can be classified into Independent Entity Mobility Models (EMMs) and Dependent Group Mobility Models (GMMs).

5.1.1. Independent - Entity Mobility Models

In EMMs, a node's movement does not control in any way other nodes' movements. Nodes move independently from each other, randomly, i.e., Random Walk Model (RWM), Random Direction Model (RDM), Gauss-Markov model (GMM), City- section mobility model (CsMM), Manhattan Mobility Model (MMM), Random Waypoint Model (RWpM) and Probabilistic Version of the Random Walk Mobility Model (PVRWM).

5.1.1.1.Random Waypoint Model

It is a model that includes pause times between changes in destination and speed. RWpM is a basic model, which describes the movement pattern of nodes where MNs randomly designate a destination in the simulation plane. RWpM became a 'benchmark' mobility model to evaluate the MANET routing protocols, because of its simplicity and wide availability. MMs are used for simulation purposes when new network protocols are evaluated.

Each MN goes to a nominated destination with a constant velocity, which each MN chooses randomly. Every node is independent. When the node arrives at the destination, it waits for a designated time and if the pause time is equal to zero, then this means that the node has a continuous mobility [63].

The two important parameters of RWpM are the velocity and pause time of each node. These parameters affect the performance of the evaluated protocol.

If the simulation of velocity is small and pause time is long, a stable topology is formed. Otherwise, a dynamic topology can be formed. Various topologies can be obtained by varying these parameters [20, 35]. Pros: Simple to implement and easy theoretical analysis.

Cons: Average speed decay problem, long journeys at low speeds, and solution use none zero min speed [16, 21, 31, 34].

5.1.1.2.Gauss-Markov Model

GMM is a model that uses one tuning parameter to vary the degree of randomness in the mobility pattern. GMM was designed to adapt to different levels of randomness, via tuning parameters [31, 45]. GMM is a different model from RWpM in terms of velocity management. In this model, the velocity of MN is correlated over time and GMM random process. GMM random process satisfies the requirements for both Gaussian processes and Markov processes. The velocity of MN at time slot **t** is dependent on the velocity at time **(t – 1).**

Therefore, GMM is a dependent mobility model, where the dependency is determined by the parameter which affects the randomness of GMM process. By tuning this parameter, different mobility models are provided [20, 21].

GMM creates movements, which are dependent on node's current speed and direction. The idea is to eliminate the sharp and sudden turns present in the RWM and RWpM, even by keeping a certain degree of randomness. Initially, each MN is assigned a speed and direction. At fixed intervals of time **n**, movement occurs by updating the speed and direction of each MN. The value of speed and direction at the $\boldsymbol{n^{th}}$ instance, is calculated based upon the value of speed and direction at the $\boldsymbol{(n-1)^{th}}$ instance and random variable using (1), and (2):

$$s_n = \alpha s_{n-1} + (1-\ \alpha)s + \sqrt{(1-\alpha^2)sx_{n-1}} \tag{1}$$

$$d_n = \alpha d_{n-1} + (1-\alpha)d + \sqrt{(1-\alpha^2)dx_{n-1}} \tag{2}$$

$\boldsymbol{S_n}$ *and* $\boldsymbol{d_n}$*: Are the new speed and direction of the MN at interval* ***n****.* $\boldsymbol{\alpha}$ *is the tuning parameters to vary the randomness, where* $(\mathbf{0} <= \boldsymbol{\alpha} <= \mathbf{1})$**.** *s and* ***d*** *are constants representing the mean value of speed and direction. As* $\boldsymbol{n} \rightarrow \infty$ *and* $\boldsymbol{sx_{n-1}}$ *and* $\boldsymbol{dx_{n-1}}$ *are random variables from a Gaussian distribution.*

At each time interval the next current location is calculated based on the current location, speed and direction. MN location can be calculated using (3), and (4):

$$x_n = \ x_{n-1} + \ s_{n-1}\cos d_{n-1} \tag{3}$$

$$y_n = \ y_{n-1} + \ s_{n-1}\sin d_{n-1} \tag{4}$$

Where, $(\boldsymbol{x_n}, \boldsymbol{y_n})$ *and* $(\boldsymbol{x_{n-1}}, \boldsymbol{y_{n-1}})$ *are the* $\boldsymbol{X}$ *and* $\boldsymbol{Y}$ *coordinates of the MNs positions.*

Pros: The movements are totally random and linear and to avoid the edges, they choose a different path.

Cons: Trip duration depends on chosen path.

5.1.1.3.Manhattan Mobility Model

The MMM uses a grid road topology. This mobility model was mainly proposed for the movement in urban areas, where the streets are in an organised manner. In this mobility model, the MNs move in horizontal or vertical direction on an urban map. The MMM employs a probabilistic approach in the selection of nodes movements, since, at each junction, a vehicle chooses to keep moving in the same direction [64].

The MNs are allowed to move along the grid of horizontal and vertical streets on the map. At a junction of a horizontal and a vertical street, the MN can turn left, right or go straight with some certainty. The node travels to a destination through the shortest path between two points. After reaching the destination, the node pauses for a specified time, then chooses another destination and repeats the process.

This procedure is repeated until the end of simulation [4]. It models factors such as: A street network, a set of buildings, destination points, safe driving characteristics (such as speed limit), and minimum distance allowed between pairs of nodes.

Pros: High realistic motion.

Cons: Complex to fully implement.

5.1.2. Dependent - Group Mobility Models

MMs Represent MNs whose movements are dependent. Used when MNs cooperate with each other to accomplish a common goal. Typical situations exist in military environments (soldiers move together), i.e. Reference Point Group Model (RPGM), Nomadic Community Model (NCMM), Column Mobility Model (CMM), Pursue Mobility Model (PMM).

5.1.2.1.Reference Point Group Model

RPGM represents the random movement of a group of MNs, as well as the random movement of each individual MN within the group. RPGM is a group mobility model where group movements are based after the path travelled by a logical centre. RPGM is used to calculate group motion via a group motion vector, i.e group mobility.

The movement of the group centre completely describes the movement of this corresponding group of MNs, including their direction and speed. Individual MNs randomly move about their own predefined reference points, whose movements depend on the group movement, RPGM can be represented mathematically in (5), and (6)[33];

$$|V_{member}^{\rightarrow}(t)| = |V_{member}^{\rightarrow}(t)| + SDR * max\ speed \tag{5}$$

$$\theta_{member}(t) = \theta_{leader}(t) + ADR * max\ angle \tag{6}$$

Where ***0 ≤ SDR****, and* ***ADR ≤ 1****.* ***SDR*** *is the speed deviation ratio and* ***ADR*** *is the angle deviation ratio. ADR and SDR are used to control the deviation of the velocity of the group members from that of the leader.*

In the RPGM, each group has a centre, which is either a logical centre or a group leader node. The assumption, is that the centre acts as the group leader. Thus, each group is continuing one leader and a number of members (MNs). The movement of the group leader determines the mobility behaviour of the entire group.

a. The Group Leader:

The movement of group leader at time **t** can be represented by motion vector '**vgt**". Not only does it shape the motion of group leader itself, but it also offers the general motion trend of the entire group. Each MN of this group deviates from this general motion vector '**vgt**'by some degree. The motion vector '**vgt**' can be randomly selected or sensibly designed, based on certain predefined routes [33].

b. The Group Members:

The movement of group members is significantly affected by the movement of its group leader. For each MN, mobility is allocated with a reference point that follows the group movement. Upon this predefined reference point, each MN can be randomly positioned in the neighbourhood.

The RPGM model is able to represent several mobility scenarios containing;

- In-Place MM: The whole region is divided into several units. A single group exclusively occupies each unit e.g. battlefield communication.
- Overlap MM: Various groups with different tasks, travel on the same area in an overlapping way e.g. Disaster relief.

- Convention MM**:** This scenario emulates the mobility behaviour in a conference. The area is also divided into many zones, while some groups are allowed to move between zones [38].

5.2. Limitations of Current Mobility Models, Topology Control, and Network Modelling

Random MMs are designed to simulate the movement of MNs in a simplified way. Because of the simplicity of implementation and analysis, they are broadly recognized [4, 33, 66]. The behaviour of the nodes (in the random mobility), are independent and there is no geographic restrictions of movement.

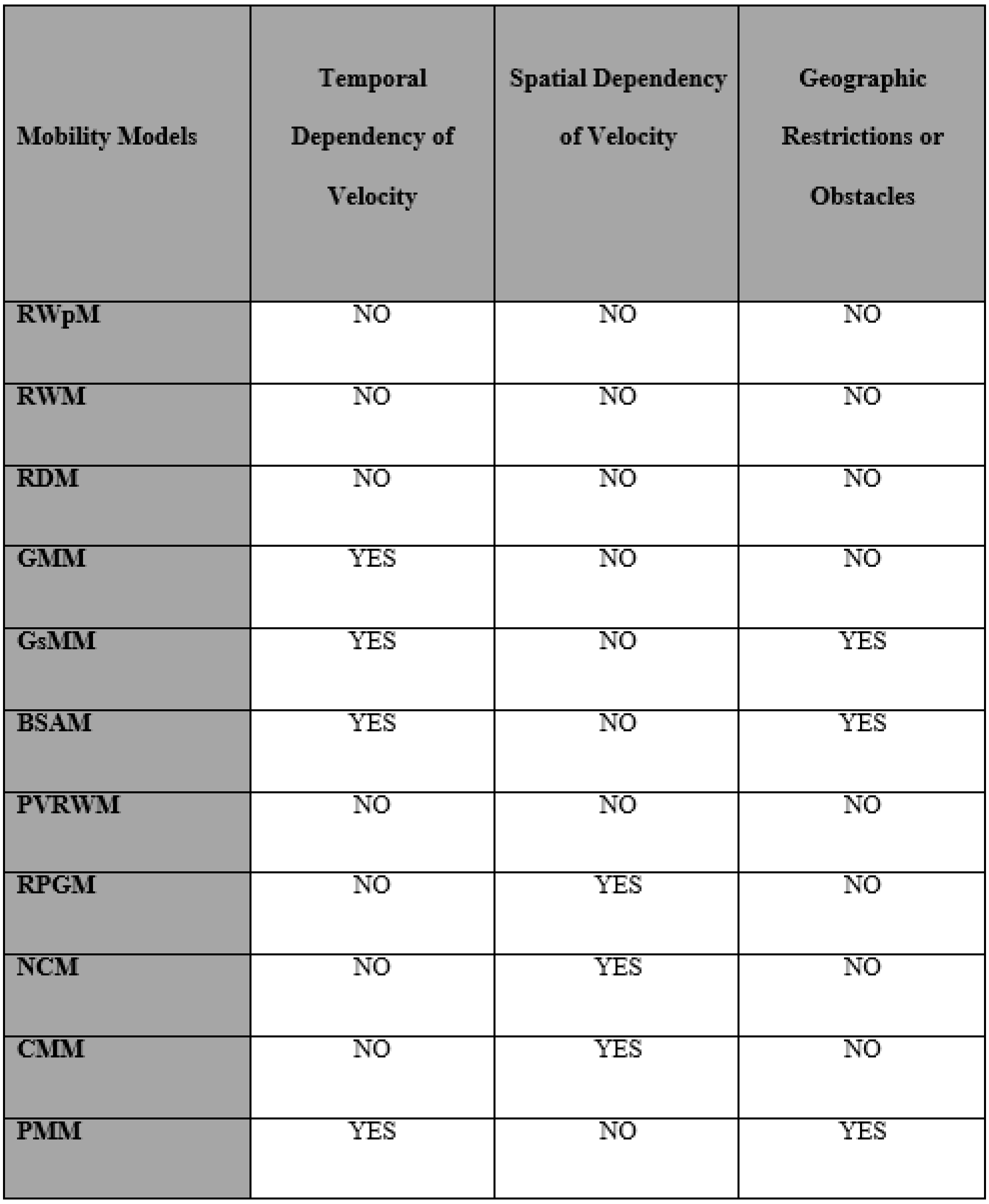
The GMM model has a temporal mobility dependency, and it is limited by the geographic restrictions of the movements. Table 8 summarises the current limitations of the mobility modelling [65].

Table 8. Current Limitations in Mobility Models

Model	**Limitations**
Random Waypoint and Random Direction Models	• It provide poor choice of velocity distribution. • The mobility behaviour of the nodes are independent. • There is no geographic restrictions of movements.
Gauss-Markov Model	• There is no geographic restrictions of the movements.
Manhattan Model	• The mobility behaviour of the nodes are independent.
Reference Point Group Model	• The mobility behaviour of the nodes are dependent.

There are no geographic restrictions of movement for the nodes in the MMM model and they are independent in their behaviour. However, they may not adequately capture certain mobility characteristics of some realistic situations Table 9, including temporal dependency, spatial dependency and geographic restriction.

Table 9. Mobility Models and Movement Characteristics



Mobility Models	Temporal Dependency of Velocity	Spatial Dependency of Velocity	Geographic Restrictions or Obstacles
RWpM	NO	NO	NO
RWM	NO	NO	NO
RDM	NO	NO	NO
GMM	YES	NO	NO
GsMM	YES	NO	YES
BSAM	YES	NO	YES
PVRWM	NO	NO	NO
RPGM	NO	YES	NO
NCM	NO	YES	NO
CMM	NO	YES	NO
PMM	YES	NO	YES

- Temporal Dependency of Velocity: In random models, the velocity of MN is a memoryless random process, i.e., the velocity at current period is independent of the previous period. Thus, some excessive mobility behaviour, such as sudden stop and sudden acceleration.
- Spatial Dependency of Velocity: In random models, the MN is considered as an entity that moves independently of other nodes [4, 64].
- Geographic Restrictions of Movement: In random models, the MNs can move freely within the simulation region without any restrictions. However, in many realistic cases, especially for the applications used in urban areas, the movement of a MN may be restricted by obstacles, buildings or streets [4, 33, 68].

The independent set and dominating set topology control models, commonly work on unit disk and undirected graphs. Where the spanning algorithms only work on undirected graphs.

Table 10 summarises the current limitations in topology control modelling. Graph matching and interference tree are new models. The approximation ratio and SINR based scheduling algorithm for preventing interference are open for the enhancements.

Table 10. Current Limitations in Topology Control

Model	**Current Status and Limitations**
Independent Set and Dominating Set	Distributed algorithms proposed in this area generally work on UDG and UG.
Spanning Tree	Distributed algorithms proposed in this area generally work on UG.
Graph Matching	There is only 1 proposed study.
Interference Trees	There is no algorithm for preventing interference.
Vertex Cover	There are few studies for constructing vertex cover in MANETs.
Steiner Tree	The node and edge weighted version of the problem is Immature.

Unit disk graph model and Undirected graph, are the most common network modules which are used in simulating simple MANET unobstructed environments.

The disadvantage of this model, in some scenarios; it does not model node and edge weights, or run probabilistic link. Also, it does not simulate nodes with different radio range in dynamic environments. Another common network model is quasi unit disk graph, which is similar to unit disk graph, but can simulate probabilistic link modelling in network with minimal obstacles [66].

Another network model which is not commonly implemented in simulating MANET due to the complexity of its design algorithm, is directed graph. Directed graph model can simulate heterogeneous MANET, and is becoming popular, thus might receive more attention in the future. Table 11 provides a summary of current limitations in network modelling.

Table 11. Current Limitations Network Modelling

Model	Current Status and Limitations
Unit Disk Graph	• Not Realistic • Lacks modelling node and edge weights. • Lacks providing probabilistic link modelling. • Lacks modelling heterogeneous ad hoc networks where nodes have different transmission range
Quasi Unit Disk Graph	Same as Unit Disk Graph except it provides probabilistic link modelling.
Undirected Graph	• Lacks using geometric properties of the wireless transmission. • Lacks modelling node and edge weights. • Lacks providing probabilistic link modelling. • Lacks modelling heterogeneous ad hoc networks where nodes have different transmission range.
Directed Graph	Same as Undirected Graph model except it models heterogeneous ad hoc network.
Weighted Directed Graph	Same as Directed Graph model except it models node and edge weights

5.3. Mobility Metrics and Steady Speed Distributions

The mobility model can be classified, based on two types of mobility metrics categories. First is direct mobility metric, and second is derived mobility metric [6].

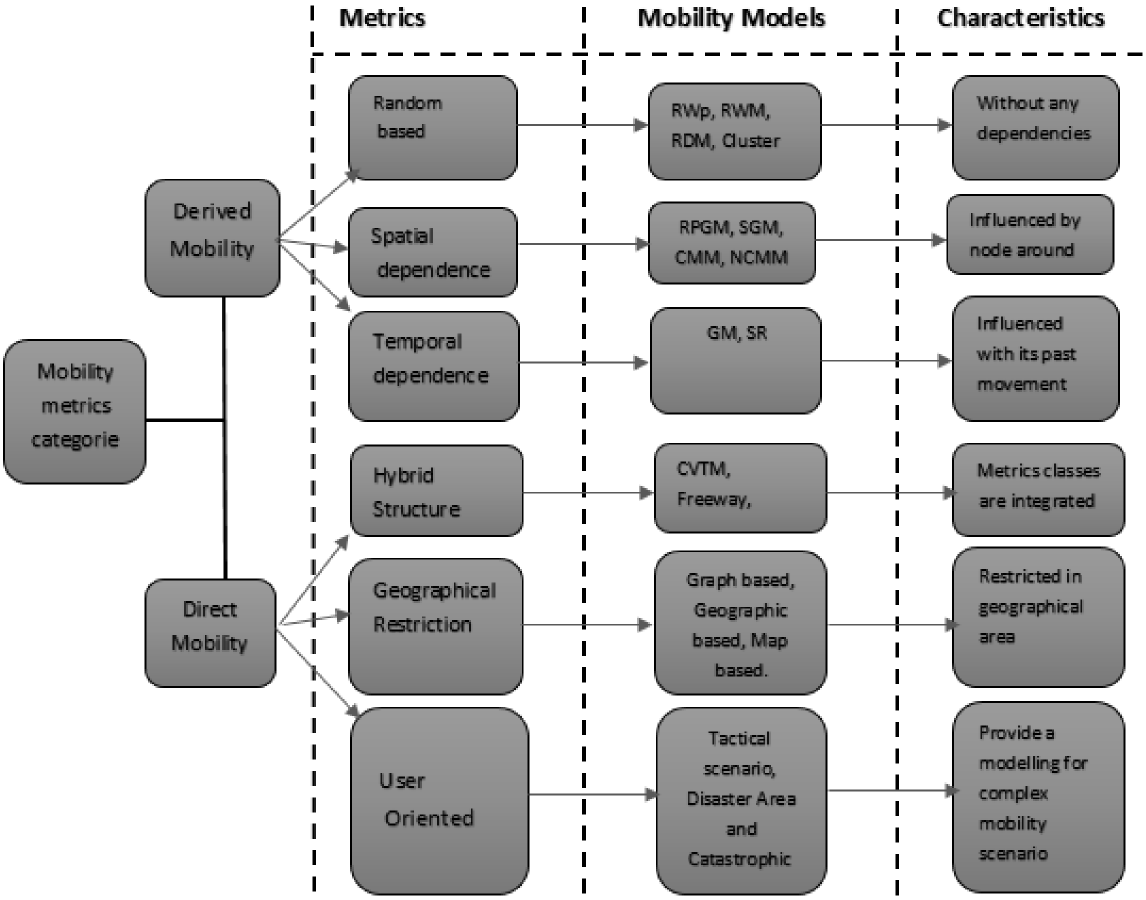
The direct mobility metrics, like host speed or relative speed, are a measurement of physical behaviour, while the derived mobility metrics, like graph connectivity, are a measurement of physical observation through mathematical modelling.

A MMs classification has been carried out based on mobility metrics, taking account of the above two categories and is arranged in Table 12 by several studies in the literature [4, 7, 10, 14, 17, 55, 64]. This section classifies general random MMs according to how the random elements of a model are chosen. The basic random elements underlying any random mobility model, include speed, distance, angle, destination and travel time.

A particular model typically selects two or more of these elements, according to some probability distribution that determines a trip. Usually the selection of these elements is independent for a single trip, and for successive trips of a single node [67].

For entity MMs the selection of these elements for different nodes is also independent. The difference between diverse MMs thus mainly lies in which of these random elements to choose, and what probability distributions to use for each choice [13, 18, 27, 33, 52].

Table 12. Classification and Characteristics of Mobility Metrics



5.4. Simulation Setup and Results

Two simulations were designed to evaluate the performance of the protocols under different MMs. One utilised various node densities and the other utilised high mobility. The common parameter setting of the simulation is shown in Table 13.

Different mobility patterns have been selected to represent real movement scenarios related to FCS. In order to explain how the mobility model impacts on the performance of protocol, various predominance metrics are used and performance differentials analysed in this section.

The MANET network simulations are implemented using OPNET Modeller simulation tool. The MMs are computed using C-code programs. Each node is then assigned a particular trajectory.

Table 13. Simulation Parameters – Mobility Models

Parameters	Value
Simulation Area	1500 x 1500 sq. meters
Mobility Models Used	RWpM, GMM, MMM, RPGM
Antenna type	Omni antenna
Traffic model	CBR
Transmitter range	300 m
Routing Protocol	DSR , AODV, DSDV, OLSR
MAC Protocols	IEEE 802.11 DCF
Data traffic size	512 bytes
Data packet rate	100 packets/sec
Simulation time	1200 sec
Number of Nodes	70
Mobility Speed	10,20,30, 40, 50, 60 m/sec
Simulation software	OPNET

MN models were constructed, that included OPNET standard IEEE 802.11 physical and MAC layers. The scenarios simulate the MANET nodes moving in a 2-D mobility region, and in this implementation the height dimension is omitted. The MMs are used to govern the movement of the nodes Figure 16, each scenario performs twenty simulation runs with different random seeds, and the mean of the metrics are compared.

The traffic destination is a random node. The traffic application is a traffic generator. This traffic generator starts at 10sec during simulation. The packet inter-arrival time is exponentially distributed with mean value of 10sec.

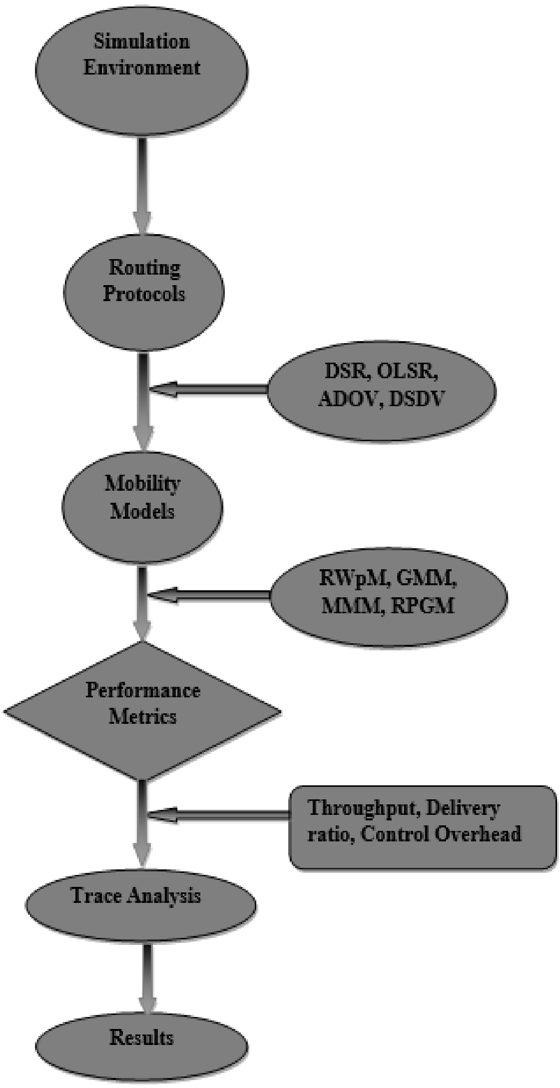
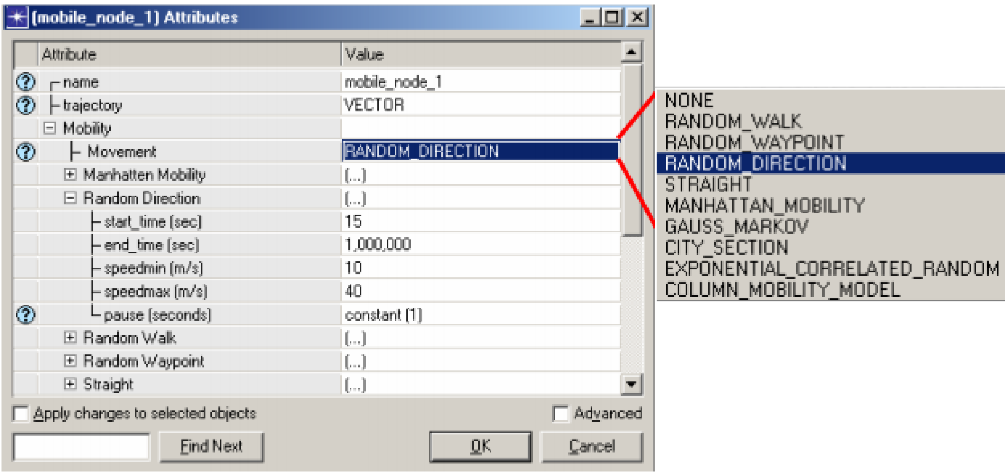


Figure 16. Implementation Design

For analysing how variation impacts speed on the performance, we set all the four models to have no pause time, and every model has the mean speed changing from 10m/sec to 60m/sec. In all patterns, 70 nodes move in an area of 1500m × 1500m for a period of 1200sec, to avoid the effect of initializing and ending, we only gather the data between 200sec – 1000sec. We generated scenario files with varying node speeds.

We considered the following performances obtained from the four MMs (RWpM, GMM, MMM and RPGM): throughput, control overhead and delivery ratio. Most of these metrics are suggested by the MANET working group for routing protocol evaluation [14, 22, 24, 45].



Attribute	Value
name	mobile_node_1
trajectory	VECTOR
Mobility	
Movement	RANDOM_DIRECTION
Manhatten Mobility	(...)
Random Direction	(...)
start_time (sec)	15
end_time (sec)	1,000,000
speedmin (m/s)	10
speedmax (m/s)	40
pause (seconds)	constant (1)
Random Walk	(...)
Random Waypoint	(...)
Straight	(...)

☐ Apply changes to selected objects ☐ Advanced

Figure 17. OPNET Mobility Models

In our simulation evolution, four routing protocols (DSR, OLSR, AODV and DSDV) were evaluated under four different MMs.

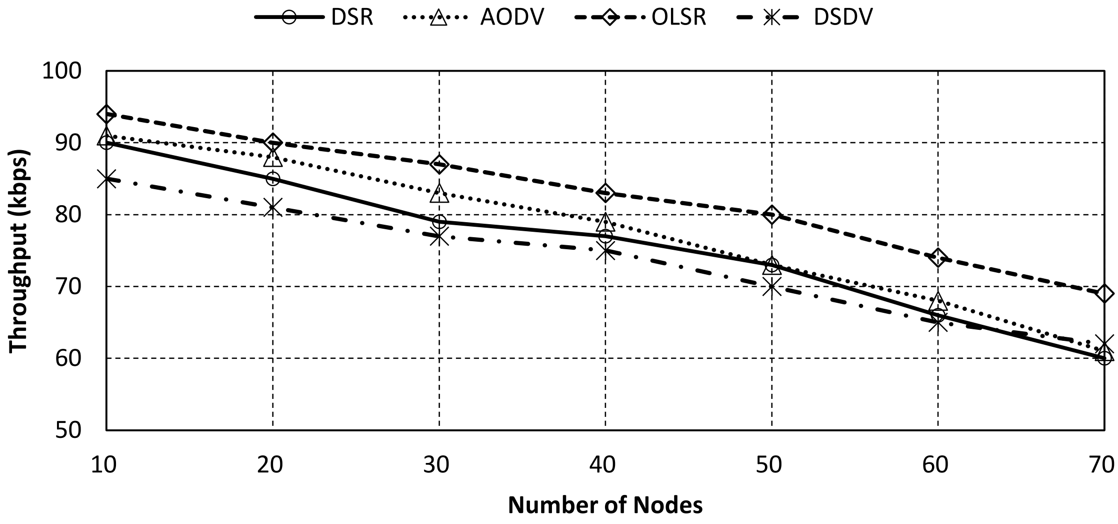
5.4.1. Different Node Density Scenarios

To evaluate a performance, along with changes in the number of nodes, extensive simulations were conducted that varied the number of nodes from 10 to 70.

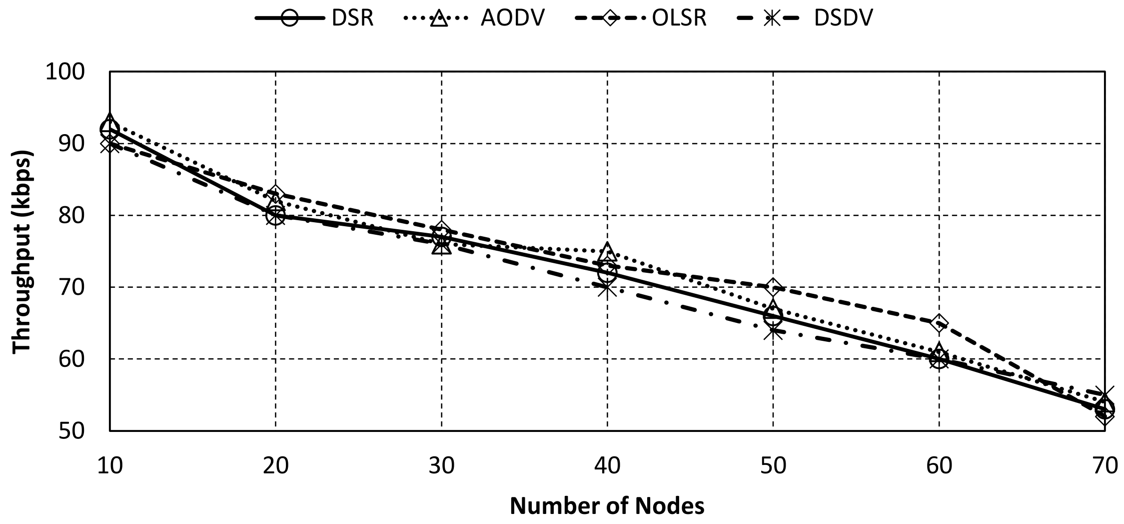
The rate of packet throughput decreased gradually, according to increasing number of nodes in all protocols (DSR, OLSR, AODV and DSDV). The error bars indicate 95% confidence intervals.

As seen in Figure 18, there are a few differences between the protocols in the section of number of nodes from 10 – 40, but large differences in section 40 – 70 nodes. OLSR successfully increased the rate of packet throughput as high as about 2% and DSR about %1. Because the number of nodes are small and nodes are of wide distribution, the number of routes are limited though a node searches for multiple routes.

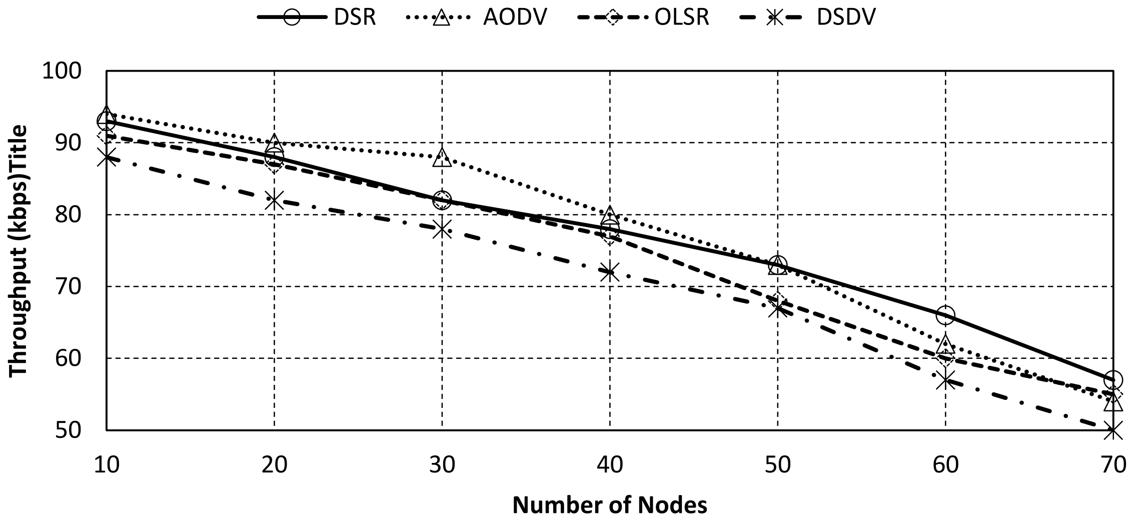
The more a node moves, the more nodes that consist of a link, are changed, and link error can be generated frequently. Therefore, OLSR packet processing ratio improves upon AODV, DSR and DSDV, in setting the shortest path.


DSR
AODV
OLSR
DSDV
Throughput (kbps)
100
90
80
70
60
50
10
20
30
40
50
60
70
Number of Nodes

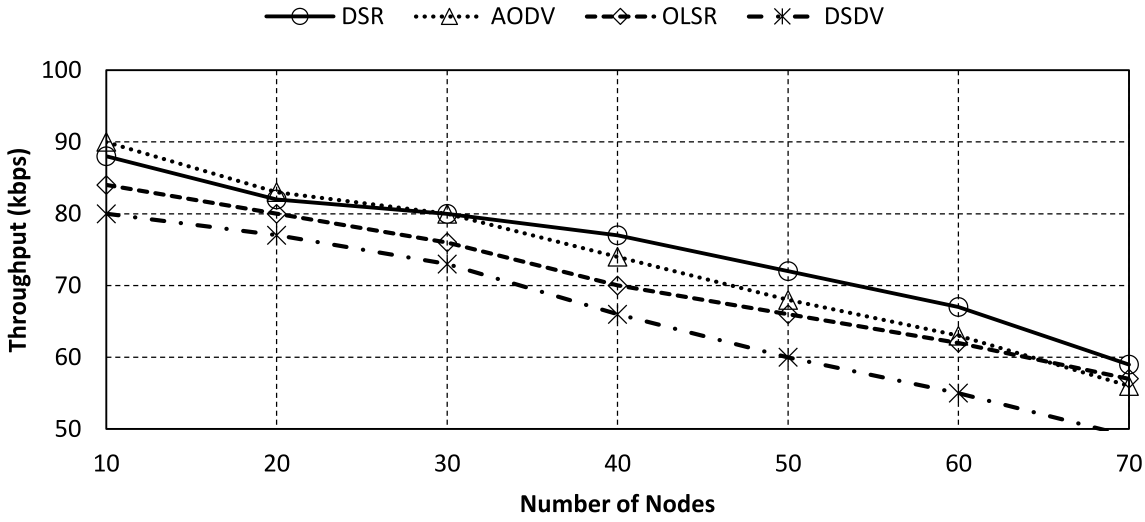
(a) RWpM


DSR
AODV
OLSR
DSDV
Throughput (kbps)
100
90
80
70
60
50
10
20
30
40
50
60
70
Number of Nodes

(b) MMM



(c) RPGM



(d) GMM

Figure 18. Throughput vs. Number of Nodes

The end-to-end delay results are shown in Figure 19 for DSR, AODV, OLSR and DSDV as a function of number of nodes in the 70-node scenarios, respectively. The error bars indicate 95% confidence intervals. In the end-to-end delay, it should take the lower performance when the number of nodes are under 30, because alternative longer routes might be selected instead of the shortest path.

The end-to-end delay is lower in the case where more than two alternative routes can be selected or many alternative routes. When the number of nodes is small, end-to-end delay in

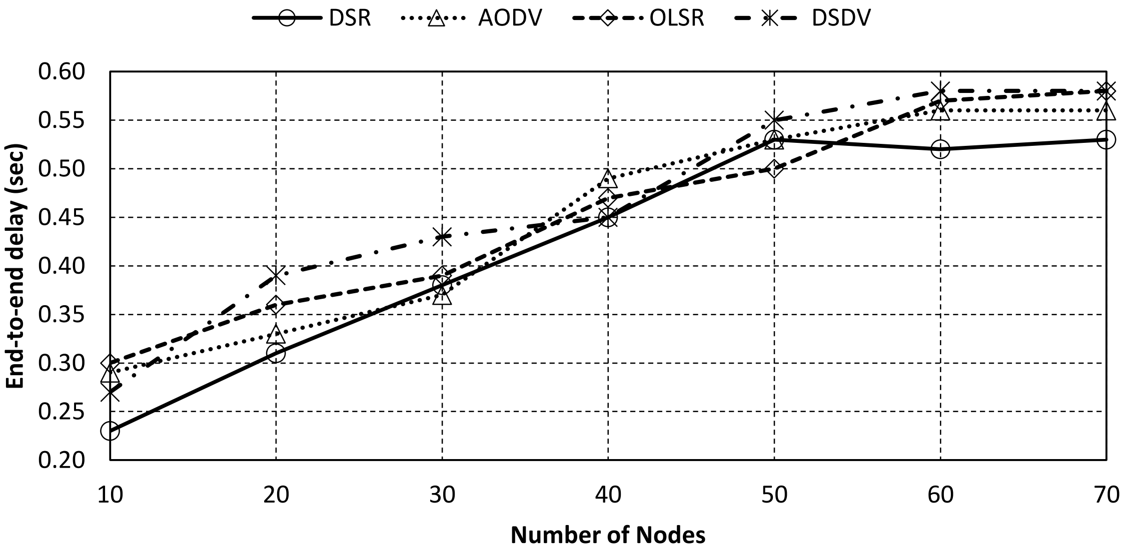
OLSR is lower, (the same result occurs in DSR), as there are few alternative routes, but if the nodes are more than 40, then end-to-end delay in AODV is lower.

The end to end delay of DSDV is higher than OLSR, AODV and DSR. The end to end delay of DSDV remains high at all speeds. Out of the four routing protocols, it is observed that AODV performs better than the other protocols in terms of the end to end delay.

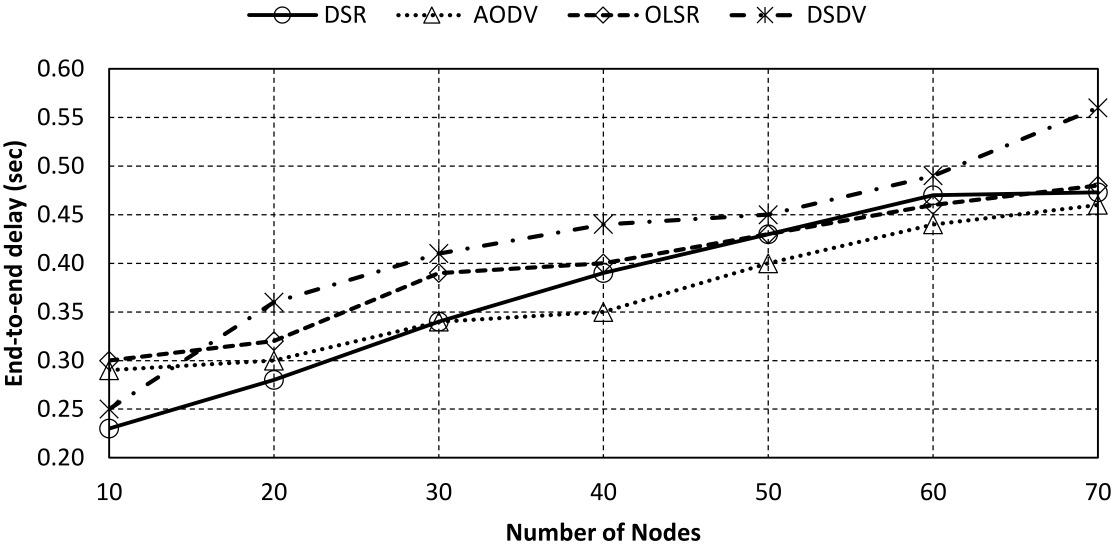
The end to end delay ratios in RWpM, for all the protocols, do not have sudden changes when the speed of the mobile node increases. All the four protocols perform well under RWpM. AODV has the highest packet delivery ratio when compared to OLSR, DSR and DSDV. In DSR there is significant decrease in the packet delivery ratio when the speed of the MN increases.

It is obvious that when the MN moves with greater speed, there are more chances of link breakage thus resulting in less packet delivery ratio.

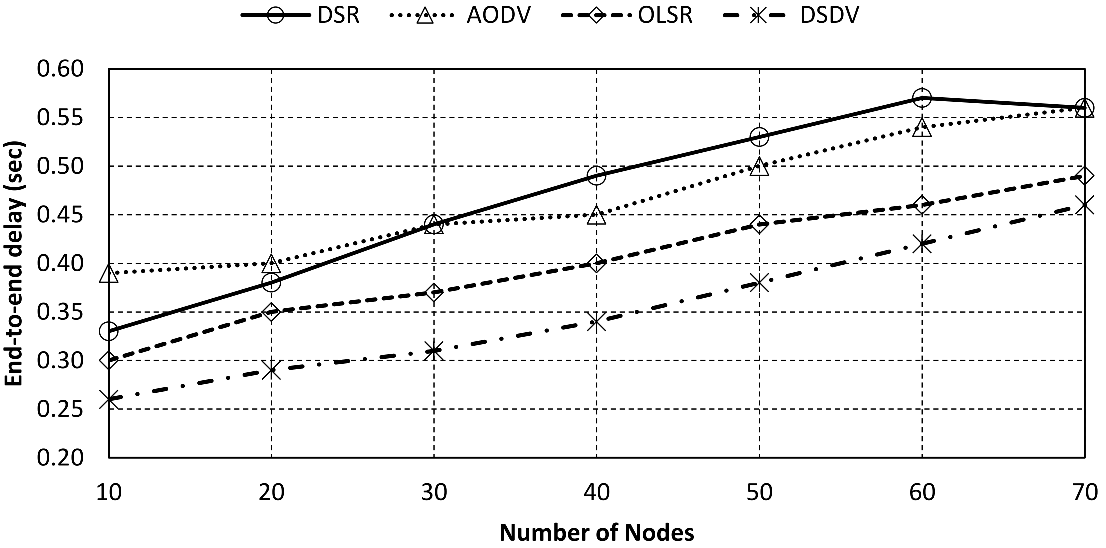
The throughput of OLSR protocol, depends entirely on the mobility model and not on the speed of the MNs. The GMM mobility model gives the better packet delivery ratio for DSR, and the MMM gives the worst packet delivery ratio, because of the lower reachability. This ordering from the best to worst, is roughly predicted by link changes. AODV is able to maintain high throughput for nearly all MMs, even as the speed increases.



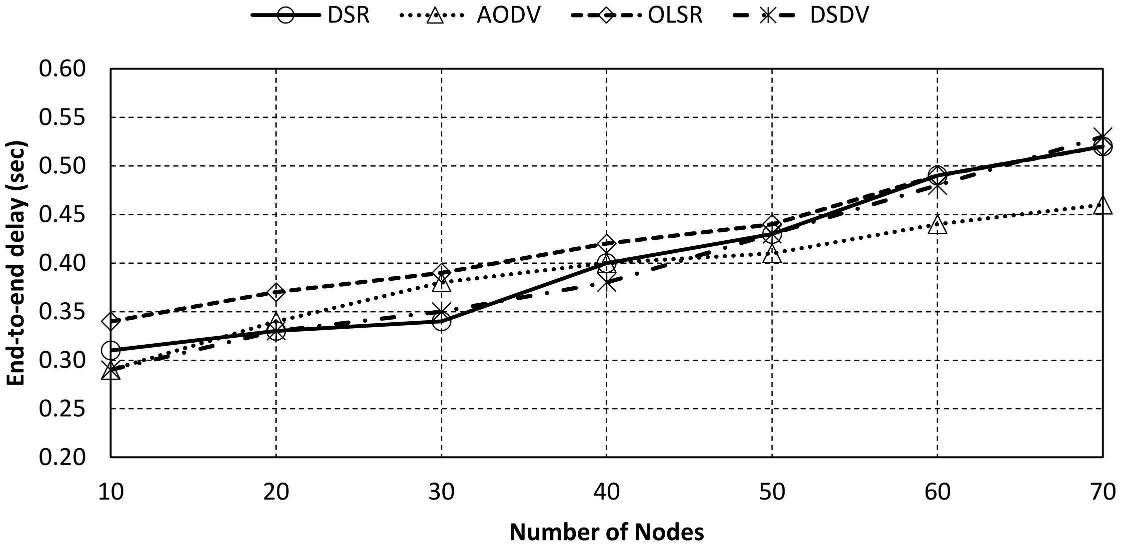
(a) RWpM


DSR
AODV
OLSR
DSDV
End-to-end delay (sec)
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
10
20
30
40
50
60
70
Number of Nodes

(b) MMM


DSR
AODV
OLSR
DSDV
End-to-end delay (sec)
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
10
20
30
40
50
60
70
Number of Nodes

(c) RPGM



(d) GMM

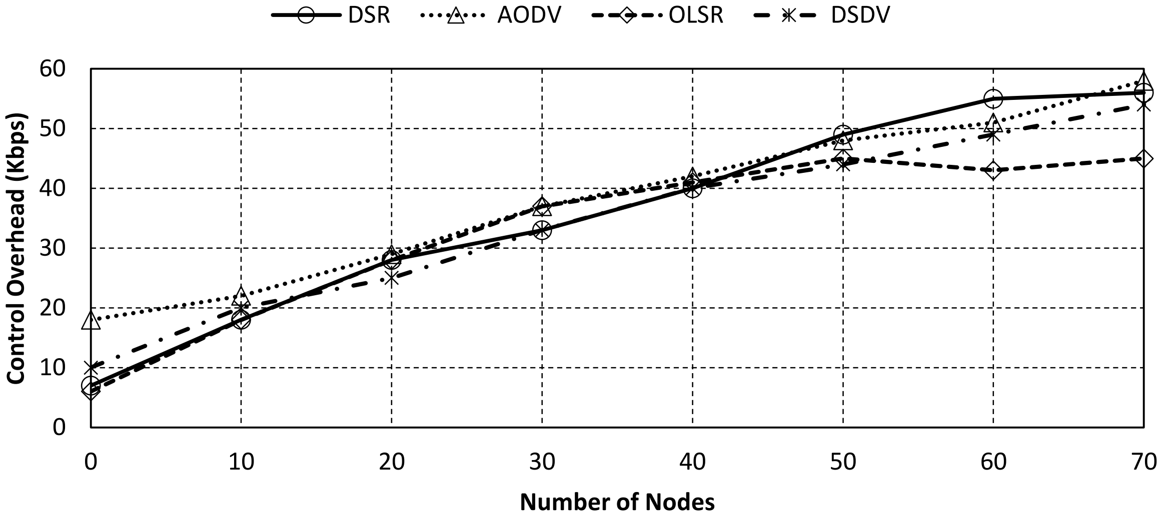
Figure 19. End-to-end Delay vs. Number of Nodes

Control packet overhead: It can be determined what the effect is per packet and the number of path searches. The results of the routing overhead are shown in Figure 20, in the 70- node scenarios, respectively.

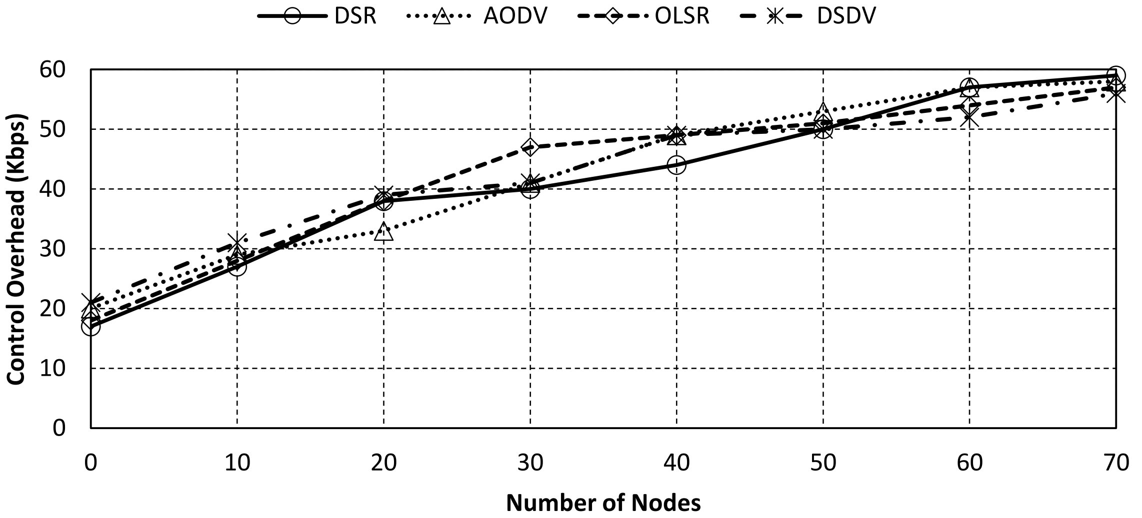
The error bars indicate 95% confidence intervals. As seen in Figure 20, they are similar until a specific number of nodes, where upon, they increases. As a result, the control packet overhead is similar between AODV, DSR and OLSR when the neighbour nodes are low in the environment, and where the total nodes are low.

In contrast, OLSR has less overhead than AODV, DSR and DSDV. Also, it was observed, that OLSR has a smaller overhead than AODV, DSR and DSDV because the number of link searches are small.

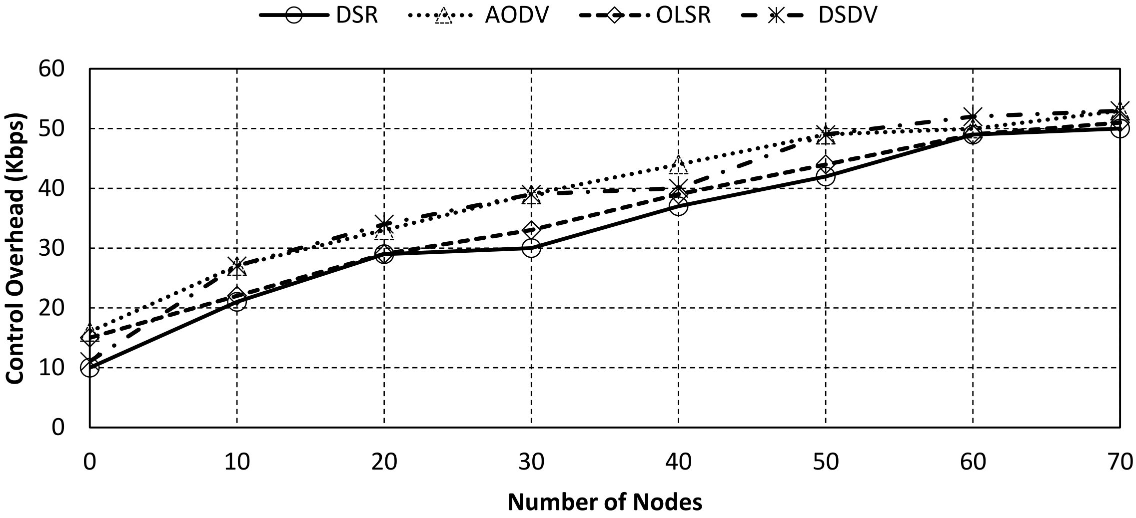
The routing overhead increases with the speed of the MNs. The RPGM model gives minimum overhead as it supports the group movement and hence, ensures more reachable nodes.


DSR
AODV
OLSR
DSDV
Control Overhead (Kbps)
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
Number of Nodes

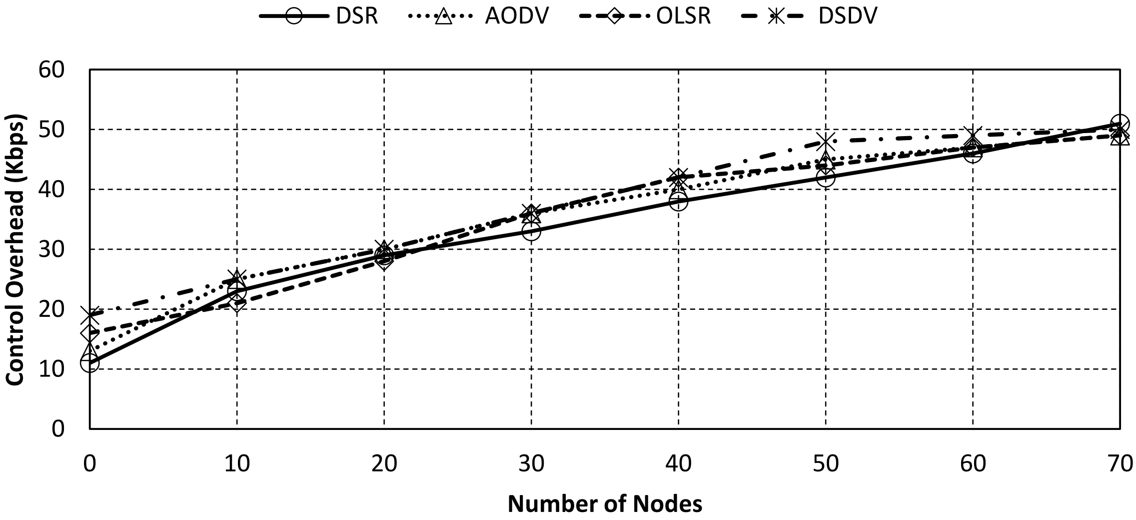
(a) RWpM


DSR
AODV
OLSR
DSDV
Control Overhead (Kbps)
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
Number of Nodes

(b) MMM



(c) RPGM



(d) GMM

Figure 20. Control Overhead vs. Number of Nodes

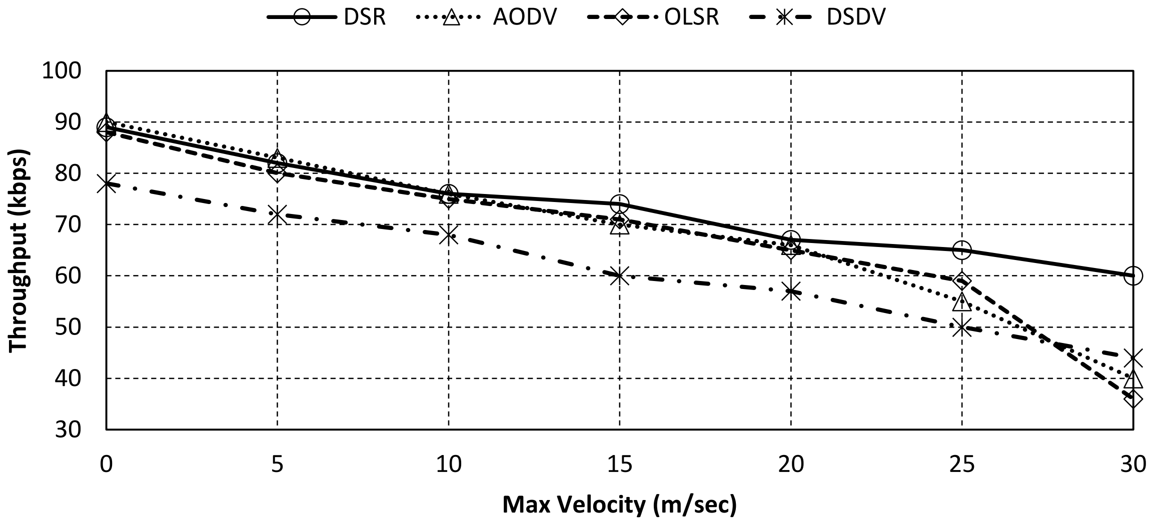
5.4.2. High Mobility Scenarios

To evaluate performance, along with changes in the maximum velocity of nodes, extensive simulations were conducted that varied the mobility of nodes from 0m/sec to 30 m/sec. The total number of nodes used was 70.

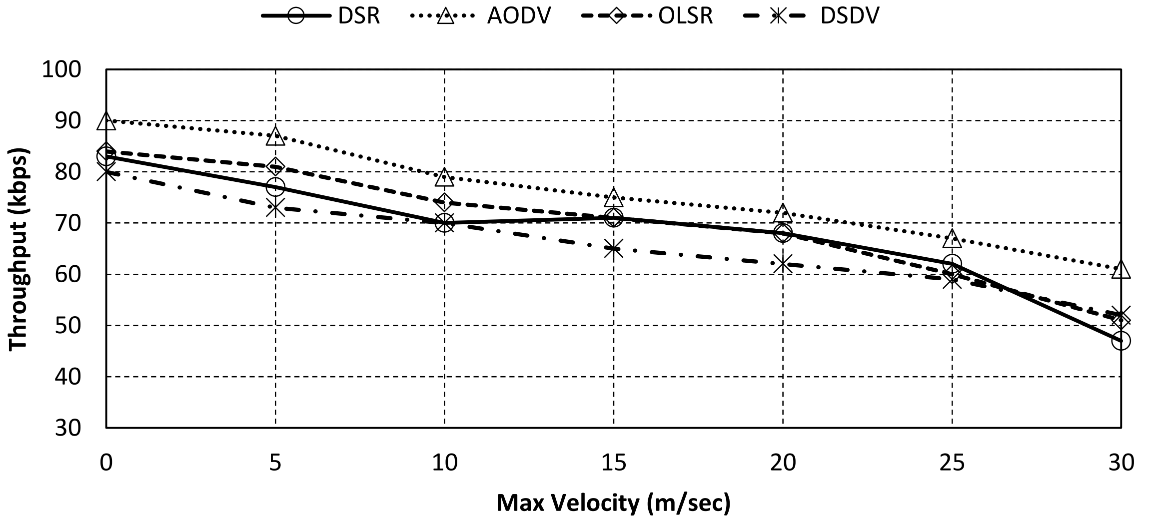
The Throughput results are shown in Figure 21, for DSR, AODV, OLSR and DSDV as a function of speed in the 70-node scenarios, respectively.

The error bars indicate 95% confidence intervals. By observing the packet processing ratio, it is seen the more a node moves, the more nodes (that consist of a link) are changed, and link error is generated frequently.

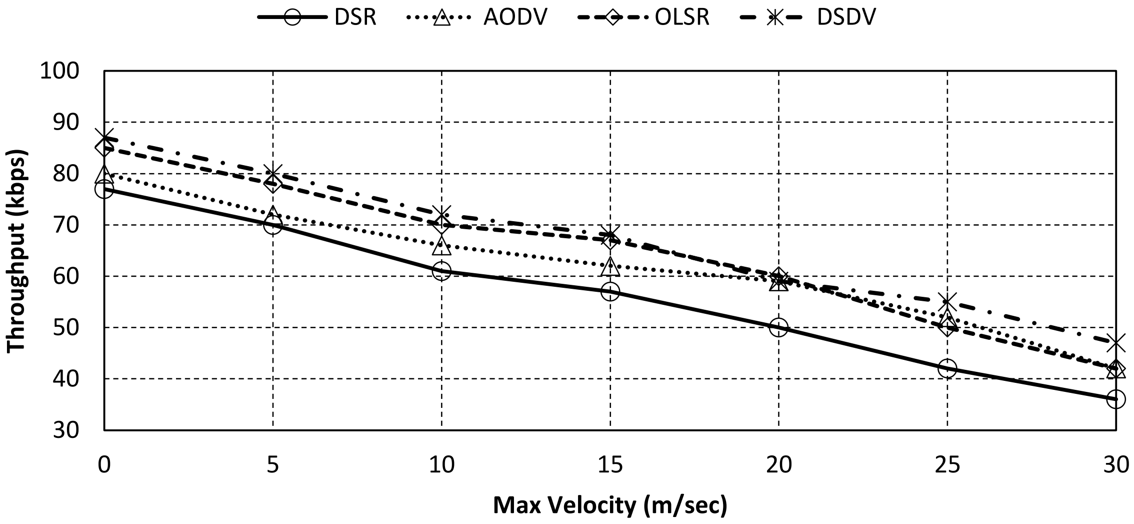
Therefore, AODV packet processing ratio is better than DSR, OLSR and DSDV, in setting the shortest path. DSR packet ratio is lower as a result of link errors getting increased because of faster node movement. But in AODV, packet throughput is decreased with smaller differences. When the Maximum velocity of nodes is 30 m/sec, the efficiency is about 1%. This is logical because large drops will, of course, mean lower throughput.



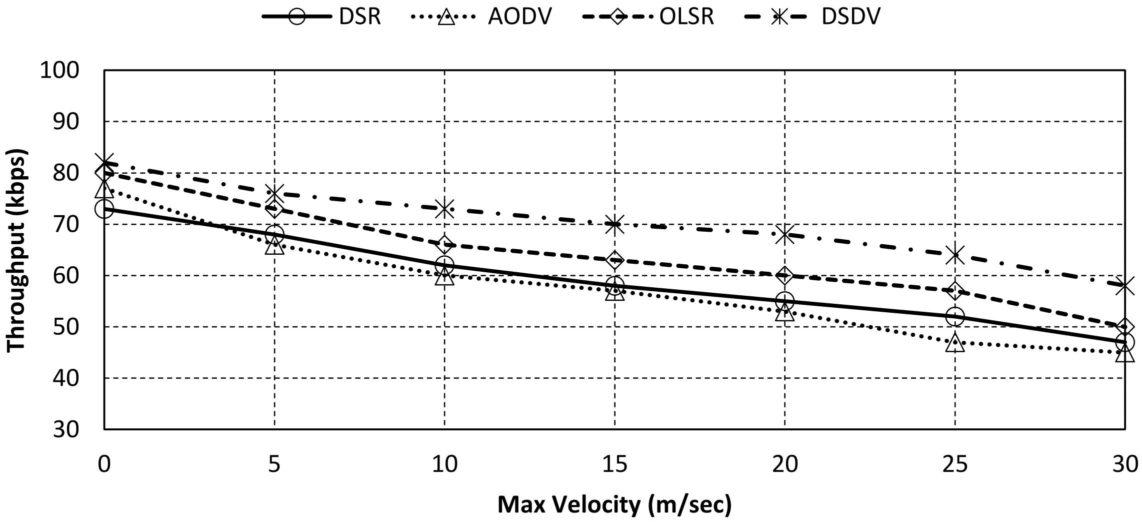
(a) RWpM



(b) MMM



(c) RPGM



(d) GMM

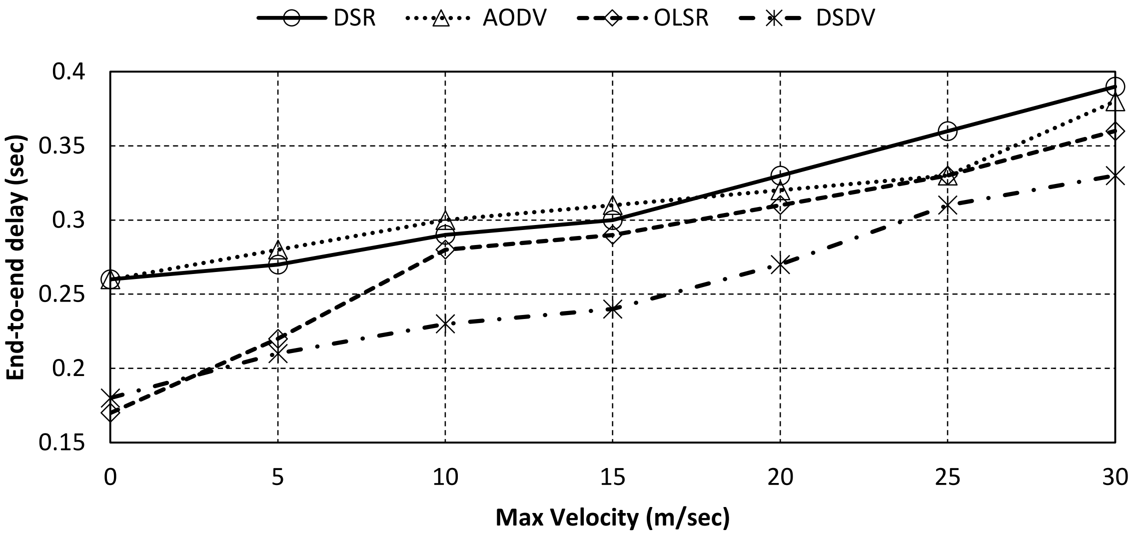
Figure 21. Throughput vs. Maximum Node Velocity

End-to-end delay: The end-to-end delay results are shown in Figure 22, as a function of speed in the 70-node scenarios, respectively. The error bars indicate 95% confidence intervals.

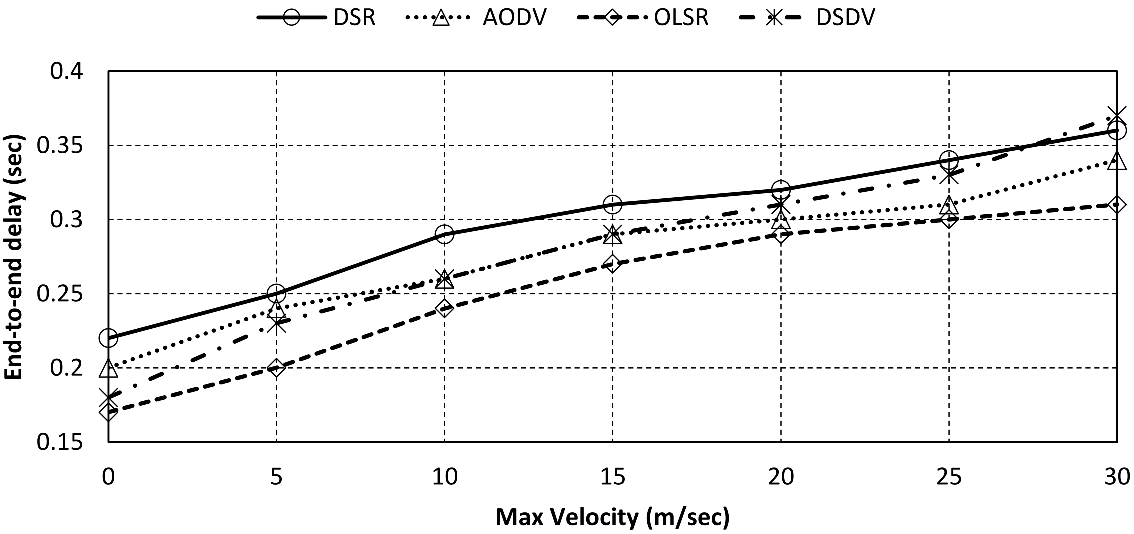
It shows that the delay time with DSR, has less increase in size than the delay time of AODV, DSDV and OLSR, according to the rate of the nodes.

The end-to-end delay time is dramatically affected when the network pace is slow rate. Because of little or no mobility of nodes, errors occur in the entire path thus there is a strong probability that it searches paths consisting of the same nodes. In this case, it cannot have great effect, even if it selects a path considering mobility.

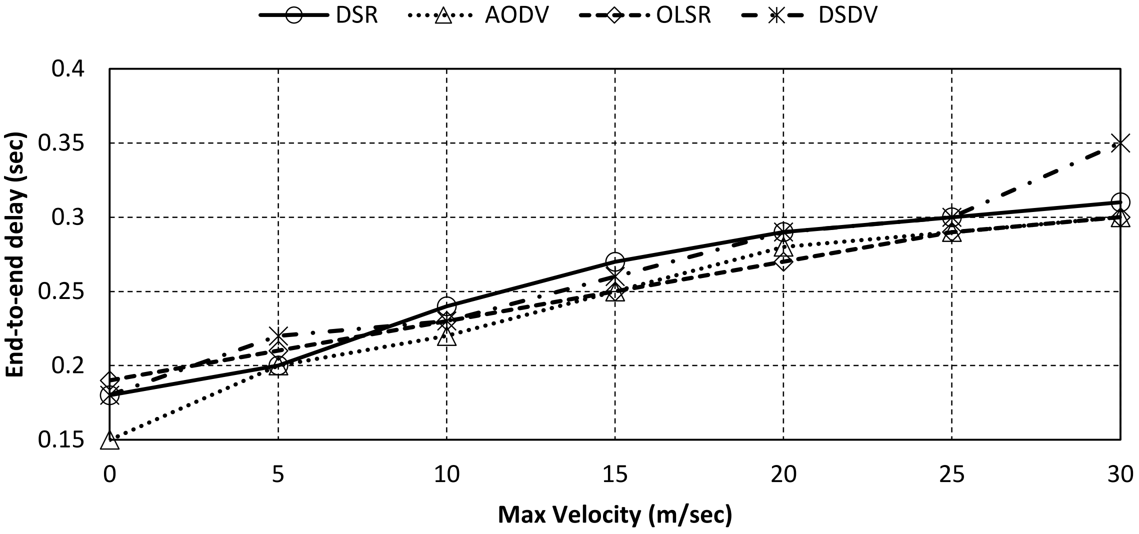
Moreover, DSR is most likely to have a larger number of nodes between source and destination node, than AODV, DSDV and OLSR, and therefore more nodes can participate in communication.



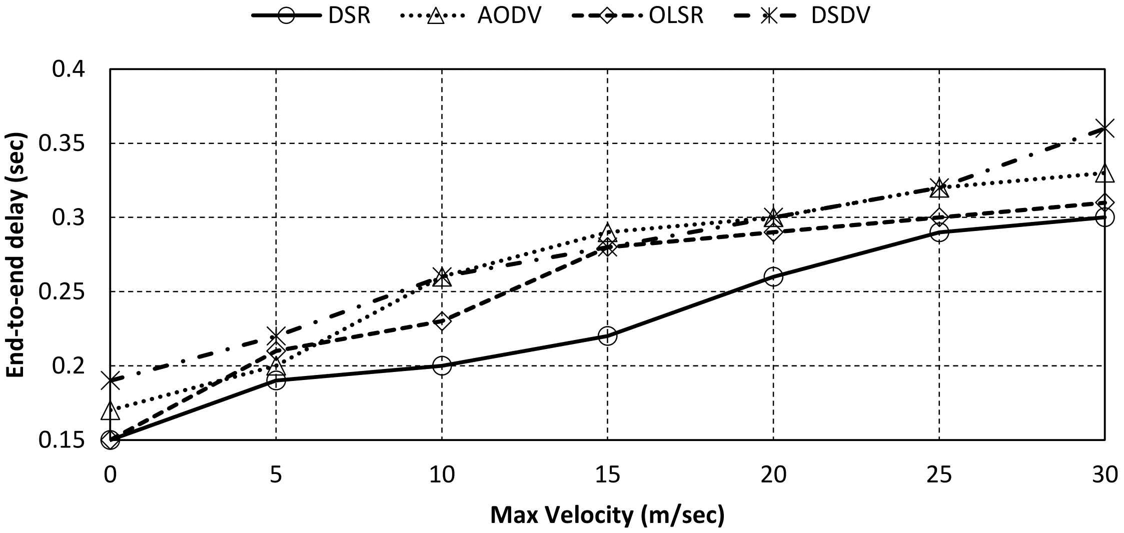
(a) RWpM



(b) MMM



(c) RPGM



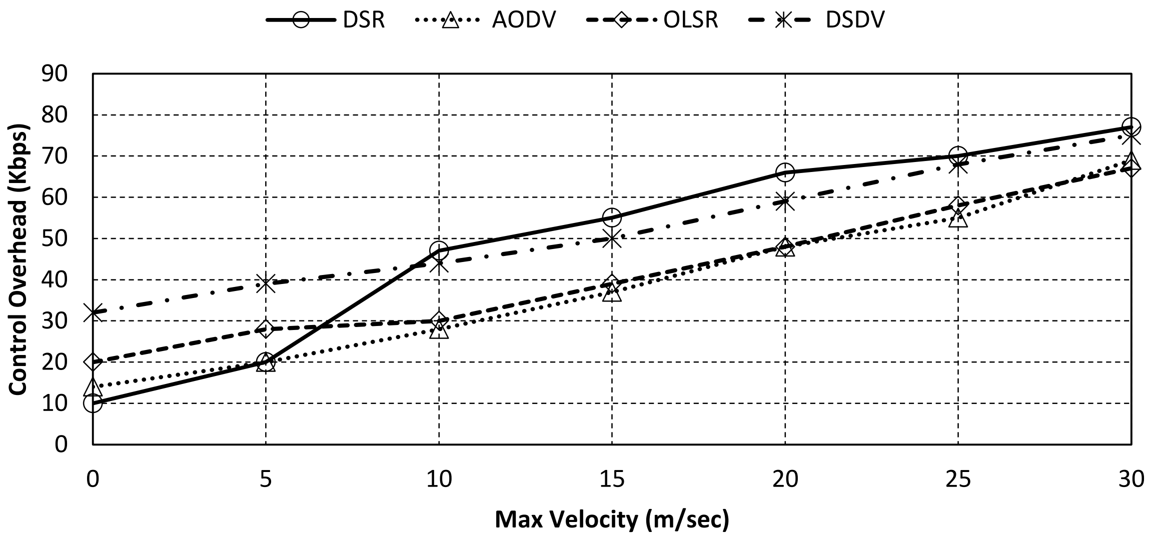
(d) GMM

Figure 22. End-to-end Delay vs. Maximum Node Velocity

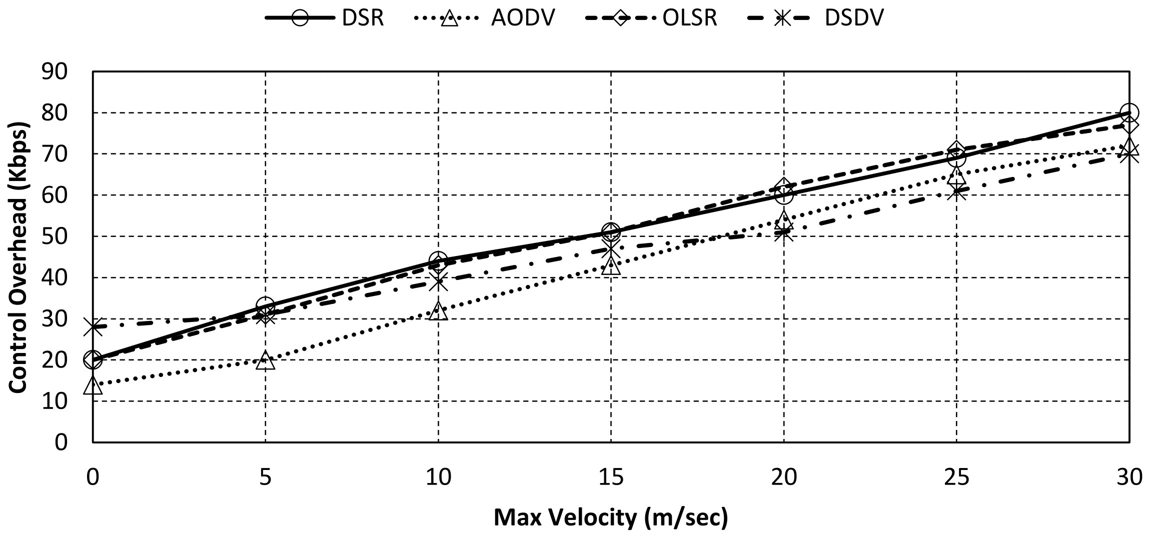
Packet overhead results can be seen in Figure 23. OLSR has a smaller overhead than AODV, DSDV and DSR, as the number of link searches are small.

Routing overhead can be determined by quantifying the effect per packet and number of path searches. The error bars indicate 95% confidence intervals.

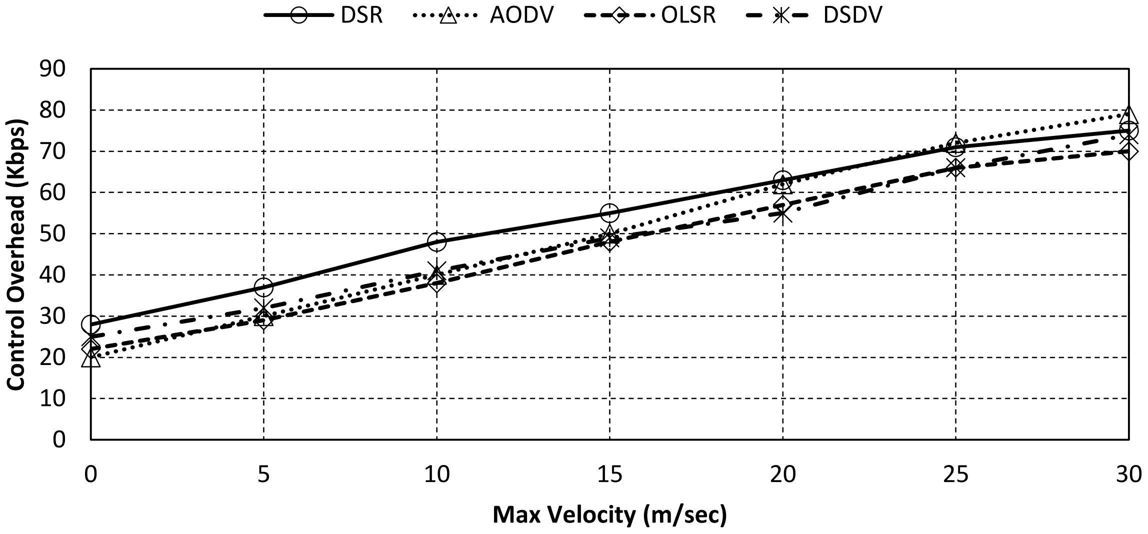
The control overheads of AODV and DSR are nearly constant, and are very close in the 70-node scenario. DSR, AODV and DSDV have large number of routing control messages due to the topology changes. RPGM model gives minimum overhead as it supports the group movement and hence ensures more reachability.


DSR
AODV
OLSR
DSDV
Control Overhead (Kbps)
0
10
20
30
40
50
60
70
80
90
Max Velocity (m/sec)
0
5
10
15
20
25
30

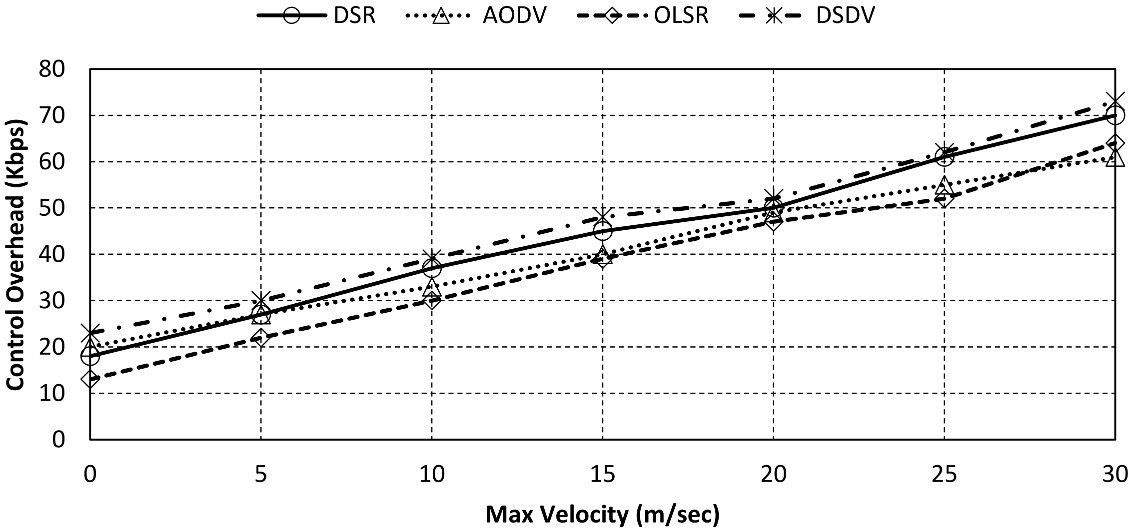
(a) RWpM


DSR
AODV
OLSR
DSDV
Control Overhead (Kbps)
0
10
20
30
40
50
60
70
80
90
Max Velocity (m/sec)
0
5
10
15
20
25
30

(b) MMM



(c) RPGM



(d) GMM

Figure 23. Control Overhead vs. Maximum Node Velocity

5.5. Chapter Summary

Simulation has become an essential tool in the design and evaluation of routing protocols for MANETs. Simulation is becoming, not only a qualitative tool, but also a quantitative. By using MMs that describe constituent movement, one can explore large systems, producing repeatable results for comparison between alternatives. In this section, several MMs have been utilised, which include both Independent and Dependant Mobility Models.

In independent entity models, the node's movement does not influence in any way other nodes movements. Nodes move independently from each other, and in Dependant Group Mobility Models, it represents MNs whose movements are dependent.

It utilised when MNs collaborate together to accomplish a common goal. Typical situations exist in military environments. Analysis has been carried out on the impact of mobility patterns, on routing performance of MANET in a systematic manner.

In the simulations, four MANET routing protocols (AODV, DSR, OLSR and DSDV) were evaluated with four mobility models (RWpM, GMM, MMM, and RPGM). In general, AODV outperforms DSDV, OSLR and DSR in terms of end-to-end delay, but the control overhead is, in most cases at least one order of magnitude higher, making it a very inefficient algorithm when the resources are limited. When comparing the on-demand algorithms, DSR outperforms AODV in terms of control overhead.

This is attributable to the high route cache hit ratio in DSR. However, AODV exhibits a better behaviour in terms of the end-to-end delay. This better performance is explained by the soft-state updating mechanism, employed in AODV to determine the freshness of the routes. For a maximum speed in the range from 5 to 10 m/sec, both DSR and AODV have better performance, in terms of end-to-end delay, for the RWpM.

As Figures 21, 22, and 23 show, with increased speed, each metric is deteriorating in some degree. These results exist, since the topology of the network is more stable with the speed increasing. As a result, the MMM model only has pause time in simulation boundary and the MNs need to keep moving in the same direction until they reach the border of the simulation area.

The RWpM model has the highest delivery ratio, lowest end-to-end delay, and shortest average hop count. The MMM model is the reverse. The GMM, RPGM models are between these two MMs.

These results exist, since the nodes in RWpM model are often travelling near the centre of the simulation area, but the nodes in MMM model can only change the direction until it reaches the border of the simulation area.

Therefore, the topology of the network can more easily be partitioned in the MMM model than in that of RWpM. Moreover, the GMM model through the probability of moving; a MN can go a longer distance before changing direction.

It alleviates the sharp turnings and sudden stops, by changing the setting of MN. The probability of the MN continuing to follow the same direction is higher than the probability of the node changing directions, the metric in GMM model is better than that of the MMM model.

Node mobility, joined with physical layer characteristics, determines the status of link connections and, therefore, the network's dynamic topology.

Link connectivity between MNs is the most important factor, affecting the relative performance of MANET routing protocols. From a network layer perspective, changes in link connectivity trigger routing events such as routing failures and routing updates.

These events affect the performance of a routing protocol, for example, by increasing packet delivery time or connectivity, and are critical to the significance of simulation results for MANET routing protocols. It has been observed, from the simulation results, how important it is to choose an appropriate mobility model in evaluating an ad hoc network protocol.

The performance results for the MANET routing protocols drastically alter due to changing the simulated mobility model. In addition, the selection of a mobility model may require a data traffic pattern, which significantly controls protocol performance. There is a very clear trend between mobility metrics, connectivity and performance.

- RWpM is used in most of simulation evaluations of ad hoc network protocols, as it can create realistic mobility patterns. The disadvantage of this model, is the straight movement pattern created by the MN to the next chosen destination in the mobile network.

- GMM provides movement patterns that can be practical in real time. In addition, GMM creates movements, which are dependent on the node's current speed and direction. The idea is to eliminate the sharp and sudden turns present in the RWM and RWpM even by keeping a certain degree of randomness.

- MMM produces Brownian motion with a small input parameter (distance or time), therefore, it is useful for evaluating a static network. In addition, it is similar to RWpM for large input parameter (distance or time) without pause times, when used in a performance evaluation for routing protocol.

- RPGM represents the random motion of a group of MNs, as well as the random motion of each individual MN within the group. The input parameters of the RPGM model allow the flexibility to implement the Column, Nomadic Community and Pursue Mobility Models. If a group mobility model is desired, it is recommended to use RPGM Model with appropriate parameters.

CHAPTER 6. LANDY PROTOCOL DESIGN

We have investigated in depth in the previous chapters, the impact of the MAC layer, Physical layer, and MM on the performance of MANET routing protocols. We also, investigated the design and examined the effectiveness of different major proactive and reactive routing algorithms in a wide range of ad hoc network simulation scenarios. This helped in designing and improving the proposed routing protocol (LANDY).

As discussed in the previous chapters, the topology based routing protocols flood the network with topology information, which results in a substantial amount of control overhead traffic that decreases the bandwidth available. In some scenarios, caching can be implemented to reduce the control overhead, but due to the dynamic network topology, this process will lead to high control overhead.

Position based routing algorithms eliminate some of the limitations of topology based routing by using geographical information about the MNs to make decisions about routing packets. This position information is provided by position service and location service. Position based algorithms (connectionless algorithm) overcame the problems related to the maintenance of the routing table in connection oriented algorithms [2, 5, 6, 8, 11, 17, 18, 21, 26, 68, 69], where the performance degrades quickly when there is an increase in the number of MNs or the speed (dynamic changing).

The position based routing algorithm has two advantages over the topology based routing algorithm:

(1) The routing algorithm does not require route establishment or maintenance.

(2) The geographical information is distributed only in the local region.

The position information is obtained by position service and location service. GPS is an example of position services, which provide information about the position of the source node. GLS is an example of a location service, which provides information about the position of the destination node. If a MN wants to send data to a destination node, it will make a routing decision based on the destination and the positions of the source one-hop neighbours Figure 24. Consequently, position based routing protocol do not require route establishment or maintenance.

Position information only needs to be distributed in the local area. Although a connectionless algorithm has no route manipulation for data transmission, it still encounters three problems: 1) Broadcast storm under high node density. 2) Local minimum problem under low node density. 3) Geographically constrained broadcast of a service discovery message.

We propose a new position based routing protocol, Local Area Dynamic routing protocol (LANDY) [55] Figure 25.

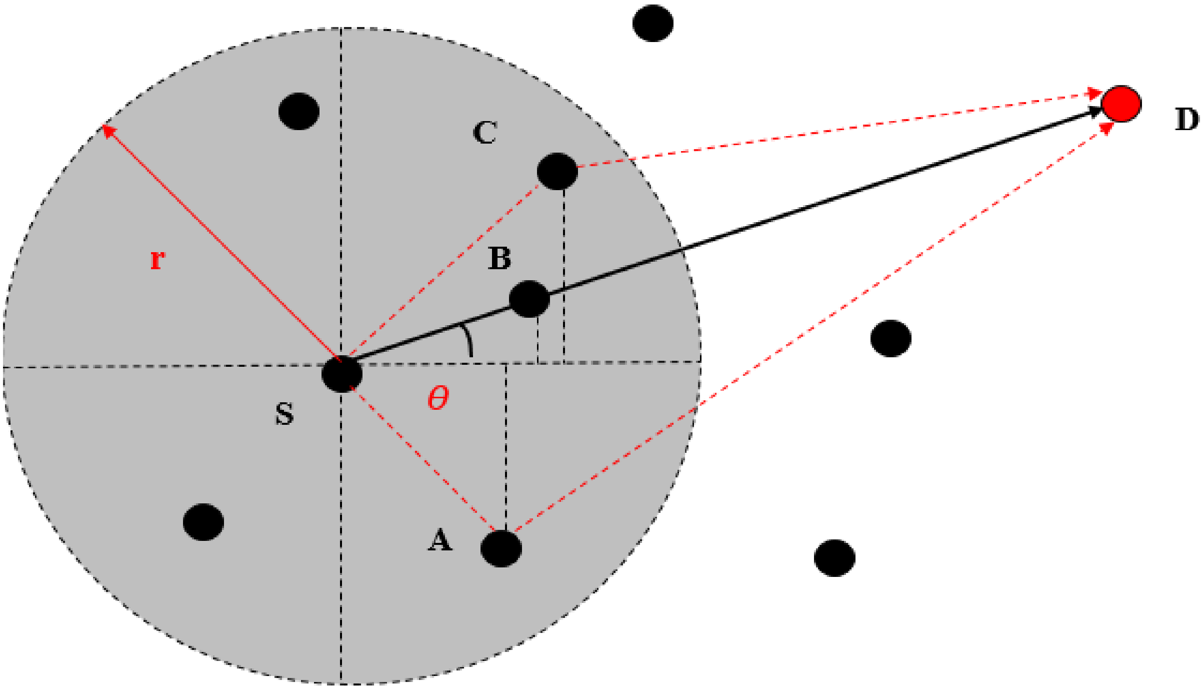


Figure 24. One - hop Communication

LANDY uses locomotion information of the MNs and the velocity of MNs, to route packets. It is assumed that nodes will have access to a position service. Obtaining location information from the position service, LANDY will employ a forwarding strategy to route packets between MNs. LANDY makes a forwarding decision based on the following:

1) Estimate the future position of the destination.

2) Estimate the future positions of the one-hop neighbours.

3) Forward the packet to the neighbour that will be closer to the destination.

If routing problems occur with the forwarding strategy, the algorithm will include a recovery mode, which will operate when the protocol recognizes that this problem has occurred. In the recovery mode, the protocol navigates the planar graph to the desired destination. The MN uses a position service (e.g., GPS) to determine its own position and location service (e.g. Grid) to get the destination position [70].

The MN maintains a locomotion components (LC). If the location based service is not available, we can forward the packet based on the cells ID (Cell unique code Identifier), utilising the cell coordinates of neighbour nodes instead of the position of the nodes.

The LC contains: The two time-stamped samples of positions (current and previous), as well as derived information about the node's speed and direction. The LC is broadcast to the node's one-hop neighbours. Each node maintains a locomotion table (LT) containing the LCs for its neighbours, to estimate the neighbour's locomotion.

Therefore, the differences LANDY has to other protocols, are it uses the locomotion prediction technique to estimate the future node position. It uses the locomotion instead of the current position to find the MNs locomotion trajectory to predict the future position of MN, which reduces the impact of the inaccuracy of neighbour's positions on the routing performance.

It avoids routing loop or routing failure using the back track process and the recovery process. It uses local locomotion to determine packets' next hop, and this increases the scalability of routing protocol. Recovery with LANDY is much faster than with other location protocols, which use mainly greedy algorithms such as GPSR.

No signalling or configuration of the intermediate node is required after failure. It allows sharing of the locomotion and velocity information among the nodes through locomotion table (LT). It uses backtrack process to the previous node (up to three nodes), for alternative paths before it switches to the recovery process.

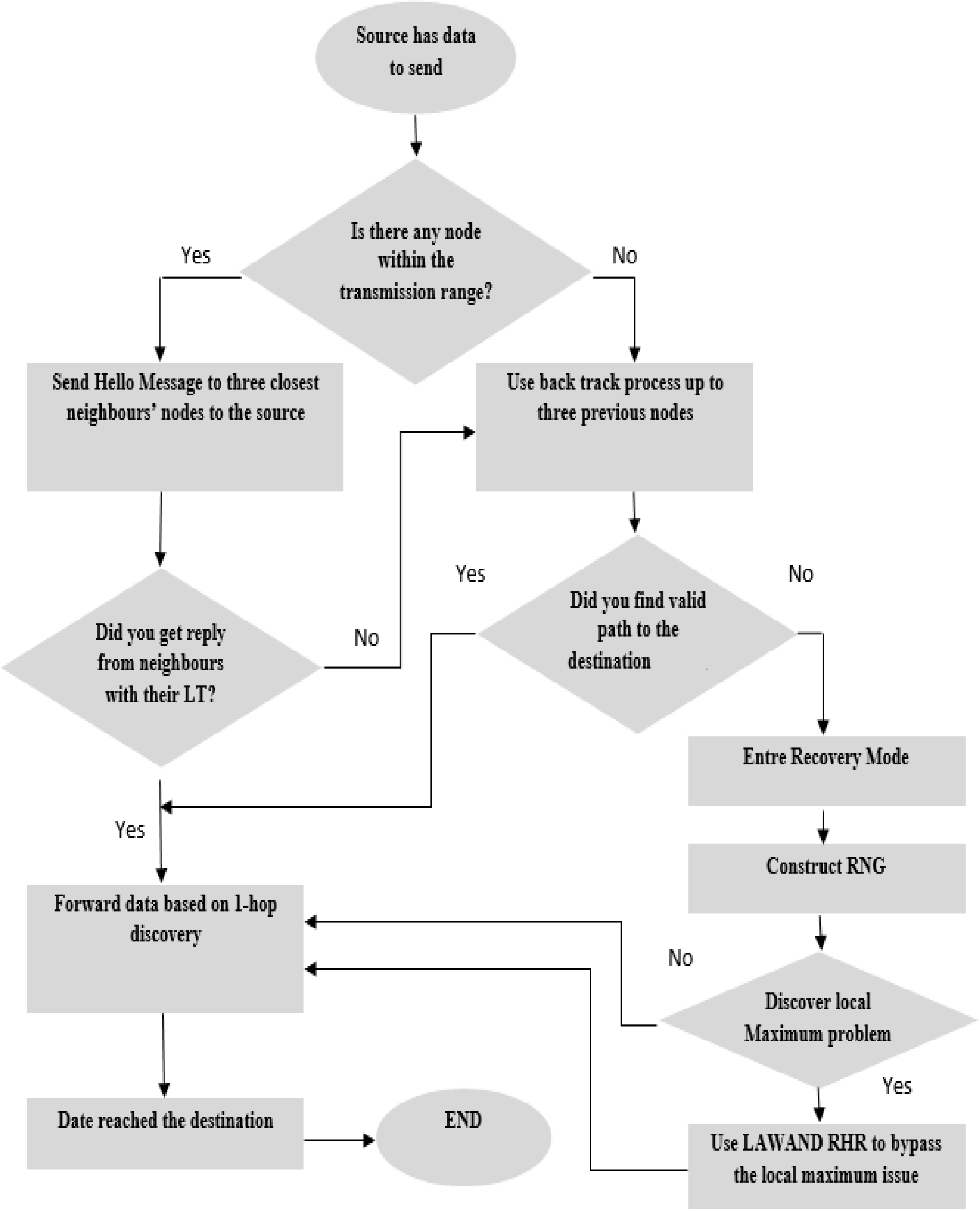


Figure 25. LANDY algorithm

6.1. Position Based Routing Protocols

Position based routing protocols use nodes location information, instead of linking information, to route the packets in MANET. In position based routing protocols, the packet source node has position information of itself, its neighbours and packet destination node. Position based routing protocols have three assumptions:

- The MN knows its location, with support of outdoors and indoors locating devices (e.g. GPS);
- The source knows the location of the destination in advance, with support from the location service.
- The MN knows the location of its neighbours, which can be achieved by periodical broadcasting and exchanging of HELLO messages with location information.

A location service provides information about the position of the destination node. This information is necessary to make a routing decision. GLS [8] is one example of a proposed location service.

A MN that wants to send traffic to a destination, will make a routing decision based on the destination position and the positions of the sender's one-hop neighbours. Therefore, position based routing does not require route establishment or maintenance, and position information only needs to be distributed in the local region. Table 14 shows comparison between major MANET positions based routing protocols.

Table 14. Position Based Routing Protocols Comparison

Position based Routing Protocol	**Pros**	**Cons**
GPSR	• Every node knows its location • Localization • A source can get the location of the destination • It use 802.11 MAC • Link bi-directionality • A node only needs to remember the location info of one-hop neighbours • Aggressive use of geography to achieve scalability.	• Use Positioning devices like GPS which is not available always. • Needs more resources. • Dead ends

	• Packets are marked by their originator with their destinations' locations. • Forwarding node can make a locally optimal, greedy choice in choosing a packet's next hop. • Forwarding in this regime follows successively closer geographic hops, until the destination is reached. • Routing decisions can be dynamically made.	
GRP	• Routing tables contain information to which next hop a packet should be forwarded • Explicitly constructed • Position of current node, current neighbours, destination known – send to a neighbour in the right direction as next hop • Use position information to aid in routing – position-based routing • It uses local information to determine paths. • Deterministically applying the right-hand or left-hand rule can result in pathological outer perimeter walks increasing hop stretch. • No explicit route discovery • Completely distributed and Low complexity • Minimal amount of control traffic • Suitable for highly dynamic environments • System is proved to be stable • Path taken by packets is near optimal	• Send to any node in a given area - geocaching • Might need a location service to map node ID to node position
Beaconless Routing	• It takes care that just one of the nodes transmits the packet. • The node located at the "optimal" position introduces the shortest delay and thus transmits the packet. • Other nodes recognize the occurrence of the relaying and cancel their scheduled transmission of the same packet. • Avoiding periodical transmission of beacons provides many advantages. • Conserving scarce battery power. • Does not use bandwidth except when needed.	• Local minima cannot guarantee delivery. • It performs routing in a distributed manner without information about neighbouring nodes. • If a node has a packet to send, it broadcasts the packet and every neighbouring node receives it. • It use Forwarder Planarization scheme to

	• Avoiding interferences with regular data transmission.	finds correct edges of a local planar sub graph at the forwarder node without hearing from all neighbours.
Geometric Routing algorithm	• Route greedily as long as possible. • Overcome 'dead ends'by use of face routing. • Efficient routing protocol in small geographical area. • Adaptively bound Searchable Area • Average-case efficiency	• Not efficient routing protocol in large geographical area. • Lower bound, worst-case optimality • Not efficient in critical density • Not efficient when graph not dense enough.
LAR	• Using location information to reduce the number of nodes to whom route request is propagated. • Location-aided route discovery based on 'limited'flooding • Local Search • Adaptation of Request Zone	• Request Zone increasing gradually • Propagation of Location and Speed Information

6.2. Position Service and Location Service

As stated in the previous section, position based routing protocols have three assumptions. We assume that the position service (assumption 1) and the location service (Assumption 2) are available in the LANDY routing protocol. If the location based service is not available, we can forward the packet based on the cells ID (Cell unique code Identifier), utilising the cell coordinates of neighbour nodes instead of the position of the nodes.

We assume the available position service and location service is on the 2-D map, since most of current MANET applications are on the ground or near the ground. GPS provides a cost-effective position service.

Communicating with the GPS satellite, the MN is able to get its accurate position. Other positioning solutions are inertial sensor, acoustic range-finding using ultrasonic 'chirps' [56]. Since our scope is limited to the LANDY routing protocol, we assume the location service is provided by the GLS [28]. GLS provides a location registration and lookup service that maps node addresses to locations.

A location service Table 15, should have the following characteristics:

- It should efficiently and accurately provide a node with the location(s) it needs to make routing decisions.
- It should be distributed, and should not rely on any special hardware or setup.
- It should be self-configuring.
- It should not introduce too much overhead.

There are four kinds of location services available:-

6.2.1. Home Agent-Based System

The location agent will assist the packet routing to the destination, which will upgrade the validity of location information caching in the network and improve the performance of geographic routing.

In home agent-based location service [11], a node chooses the location scope where it first joins the MANET as its home agent. It periodically sends location update to all the MNs in its home agent. Because the location of home agent is announced to all the other nodes in the beginning, all following queries can be sent to its home agent and get the corresponding reply.

The disadvantages of this scheme are:

- Inefficiency: Suppose the node moves far away from its home agent, location updates would have to go across long distance.
- High requirements on memory: Every node has to keep every other’s home agent.

6.2.2. DREAM System (Distance Routing Effect Algorithm for Mobility)

It uses the location to forward the packet towards the direction of destination. DREAM was the most intuitive method proposed as [9], in which MNs broadcast their location information throughout the MANET periodically. As a result, the source knows the up-to-date location of the destination before data transmission.

Each node may maintain a location table about the position of all nodes of the network and frequently flood a location packet, called control packet, to update the position information maintained by its neighbours. Although it may consume much bandwidth, it’s very simple, robust and easily implemented.

6.2.3. Quorum System

Quorum systems can provide the algorithms with the lowest, or near lowest, active ratios, as they have the optimal or near optimal quorum sizes. Quorum system originates from information replication in databases and distributed systems, and could be applied to location service.

In quorum system, some MNs are chosen to form a backbone network in the MANET. These backbone nodes are further divided into several quorums, such that the intersection of every pair of quorums is non-empty.

In Quorum system, the mobility database storing the location information of a MN can be selected adoptively from the QS, by considering the gravity of locality.

6.2.4. Grid System

Grid uses geographical forwarding to take advantage of the similarity between physical and network proximity. A source must know the geographical positions of any destination to which it wishes to send, and must label packets for that destination with its position.

Grid system [8] is a hierarchical location service. Grid protocol tracks the location of MNs with its scalable location service architecture, and forwards the packets through geographic forwarding.

Each MN is assumed to be GPS capable, and periodically updates a small set of other nodes (its location servers) with its current position.

Grid is self-containing. It is independent of unicast routing protocols, which means location updates and location queries are forwarded based on location information as well.

Table 15. Present Location Services Characteristics

Criterion	**DREAM**	**Quorum system**	**GLS**	**Homezone**
Type	All-for-all	Some-for-some	All-for-some	All-for-some
Communication complexity (update)	$O\ (n)$	$O\ (\sqrt{n}\ )$	$O\ (\sqrt{n}\ )$	$O\ (\sqrt{n}\ )$
Communication complexity (lookup)	$O\ (c)$	$O\ (\sqrt{n}\ )$	$O\ (\sqrt{n}\ )$	$O\ (\sqrt{n}\ )$
Time complexity (update)	$O\ (\div n)$	$O\ (\sqrt{n}\ )$	$O\ (\sqrt{n}\ )$	$O\ (\sqrt{n}\ )$
Time complexity (lookup)	$O\ (c)$	$O\ (\sqrt{n}\ )$	$O\ (\sqrt{n}\ )$	$O\ (\sqrt{n}\ )$
State volume	$O\ (n)$	$O\ (c)$	$O\ (\log(n))$	$O\ (c)$
Localized information	Yes	No	Yes	No
Robustness	High	Medium	Medium	Medium
Implementation complexity	Low	High	Medium	Low
$Abbreviations: n = number\ of nodes, c = constant$				

6.3. Graph Theory - Planar Graph

A graph is planar if it can be drawn in the plane without edges crossing. Further, a graph is planar if it has an embedding in the plane, in which each vertex is mapped to a distinct point **P(v),** and edge (**u, v**) to simple curves connecting **P(u), P(v)**, such that curves intersect only at their endpoints.

Below are the major graph theory which represent MANET:

- The Relative Neighbour Graph (RNG) [57], is a graph in which an edge (**u,v**) exists between vertices **u** and **v** if the distance ||**uv**|| is less than, or equal to, the distance between every other vertex **w**, and whichever of **u** and **v** is father from **w**.

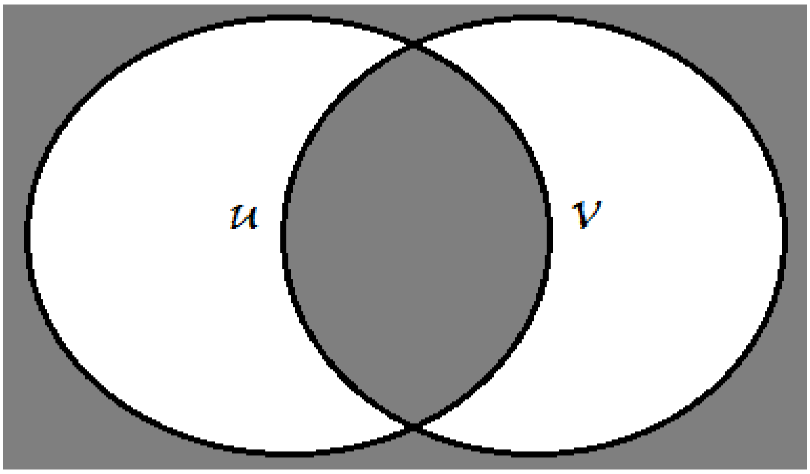


Figure 26. Relative Neighbour Graph

- The Garbriel Graph (GG), is a graph in which an edge (**u,v**) exists between vertices **u** and **v** if no other vertex **w** is present within the circle whose diameter is ||**uv**||.

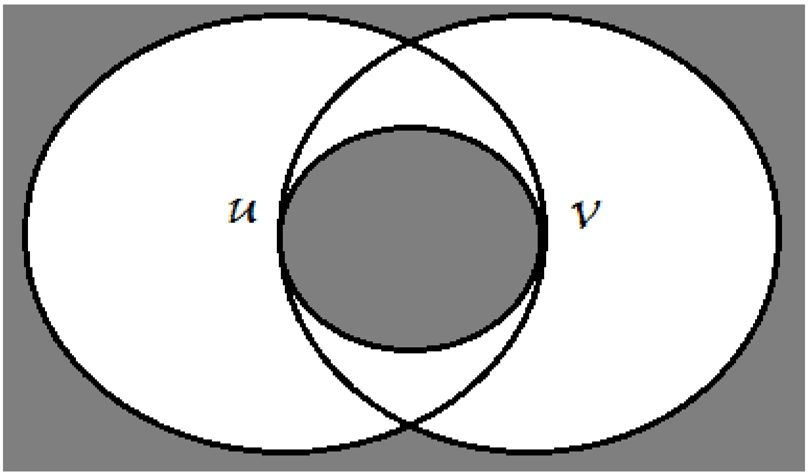


Figure 27. Gabriel Graph

- The Minimum Spanning Tree (MST), is a graph that contains all vertexes and has a minimum sum of edge weight.

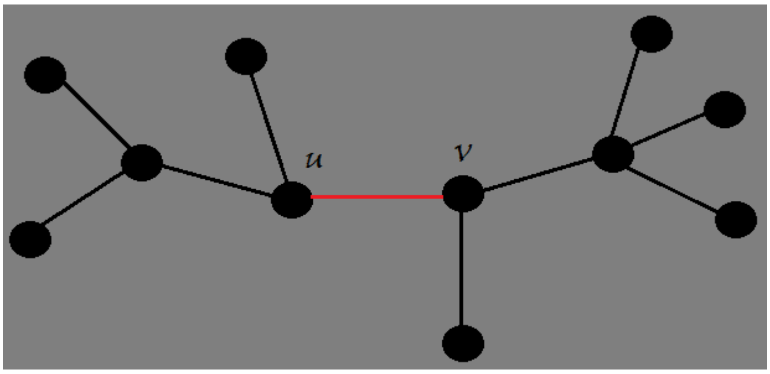


Figure 28. Minimum Spanning Tree

- The Delaunay Triangulation (DT), is a triangulation, if the circumcircle of each of its triangles does not contain any other nodes in its interior.

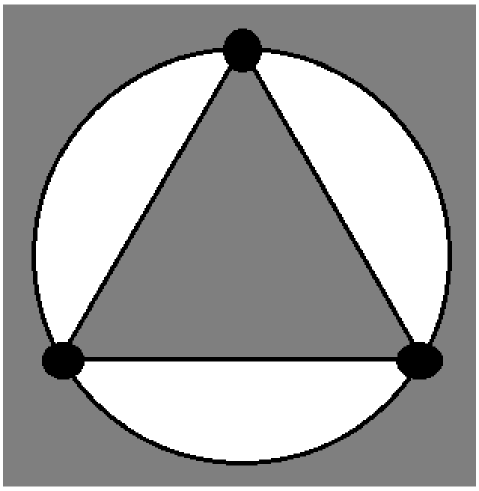


Figure 29. Delaunay Triangulation

- Unit disk graph (UDG), is a graph which has an edge (**u,v**) if (and only if) the Euclidean distance ||**uv**|| between u and **v** is less than one unit.

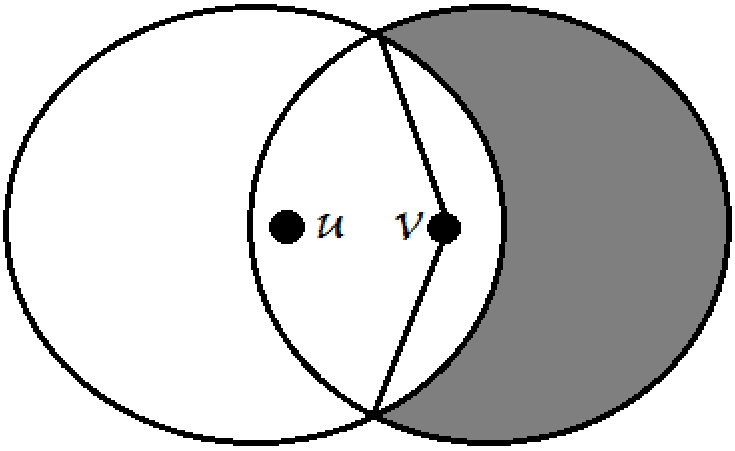


Figure 30. Unit Disk Graph

6.4. Forwarding Strategy

Different forwarding strategies are available to forward the packets Figure 31. The most competing forwarding strategy is Greedy Packet Forwarding. When a MN starts sending a packet or an intermediate node receives a packet, the node forwards the packet to a neighbour lying in the general direction of the recipient. Ideally, this process can be repeated until the recipient has been reached.

6.4.1. Random Neighbour

It is a strategy to forward packets to random selected neighbours closer to the destination [6]. This strategy minimizes the accuracy of information needed about the position of the neighbours and reduces the number of operations required to forward a packet.

6.4.2. Greedy Forwarding

The routing decision at a node in the network is only based on its own position, the position of its single hop neighbour nodes and the position of the destination node.

Greedy routing does not require the establishment or maintenance of routes. The nodes neither have to store routing tables, nor do they transmit messages to keep the routing tables up to date, and no global information about the topology of the network is needed.

The sender of a packet includes the approximate position of the recipient, in the packet. Greedy Forwarding forwards the packet to the forwarding node among all neighbours so that the distance from the forwarding node to the destination is shortest.

6.4.3. Compass Routing

Another forwarding strategy is compass routing [15], which selects the neighbour closest to the straight line between sender and destination. It intends to forward a message towards the closest direction to the target node on each routing step.

Because in such structures the best direction is not always present or is congested, the algorithm highlights a range of possible directions around (+, -) 90 degrees.

6.4.4. Most Forward Within R (MFR)

MFR [9] forwards the packet to the node that makes the most progress towards (is closest to) the destination.

6.4.5. Nearest with Forward Progress (NFP)

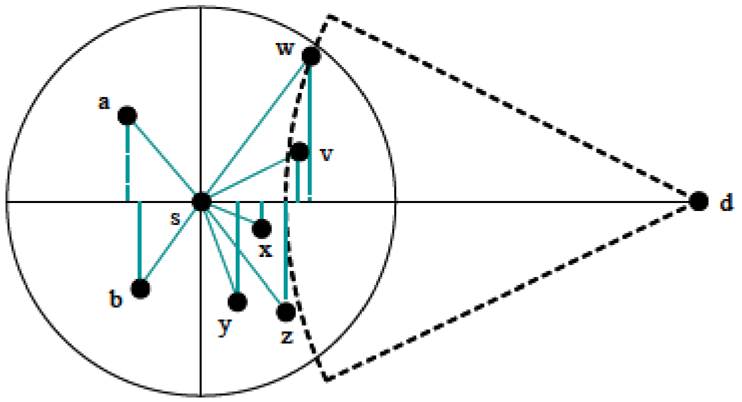
In NFP [24], the packet is forwarded to the nearest neighbour of the sender which is closer to the destination.

6.5. LANDY Network Initialization and Process Analysis

It is assumed that the routing area is a two dimensional plane. The entire network is divided into several non-overlapping triangular cells, and each cell has CCID (Cell Code Identifier). LANDY`s algorithm allows each MN to determine the cell where it resides during the life of the network, based on the information provided by LT and the GPS device equipped with each node.

Let **n** is the number of MNs in the region and **Ni** is the scale of the MN, **Sj** number of neighbour MNs to the source node **S**, where **Ni** < **n (CCID). k** is the existing number of MNs in the request region (CCID) at the time **t0** and **k' (=k+Δk)** is the number of MNs in that region at time **t1**, where **k<=n (CCID), Δk** can be either positive or negative. **uv** is the number of edges in the given network RNG, **uv' (<=uv)** is the number of edges in the request region, **bp** is the number of backtrack packets received by the node **S** and **l** is the length of the path (in hops) from the source node **S** to the destination node **D**.

The network layer interacts with the MAC layer to estimate the bandwidth while taking into consideration the activities of neighbouring nodes, which makes LANDY more practical.



Random Forward Progress (RFP): x, y, z, v, w
Most Forward within R (MFR) : w
Nearest with Forward Progress (NFP): y
Greedy: v
Compass: x

Figure 31. Forwarding Strategies

6.6. Locomotion Predication of Mobile Nodes

Most MANET geographical protocols (position based) utilise the current position of the node, the neighbours and the destination, to determine the packet's forwarding node. The position of the transmitting node is received from the position service.

The positions of the neighbours are distributed by an intermodal mechanism such as HELLO message broadcasting. The destination position is learned by the location service, and may take time to update.

However, the position information of neighbours and destinations will not be accurate after some time, and this may result in routing loop or routing failure.

With three samples of node position, it can estimate speed and direction and use this derived information to predict the locomotion in the near future of the MN. The forwarding decisions are made based upon the locomotion of the MN, the neighbour nodes and the destinations, and it can be shown that mobility characteristics will affect MANETs.

On the other hand, the approach of using locomotion prediction has the advantage of fast and accurate routing over other position based routing algorithms in mobile scenarios. Figure 32, illustrates the locomotion prediction of the LANDY protocol.

The source node (**S**) intends to send a data packet to the destination node (**D**). There are six one-hop neighbour nodes, **a, b, c, d, e, f** within the radio range of the source node. A HELLO message broadcasting mechanism, makes all nodes aware of their neighbours' locomotion information.

Each MN broadcasts a HELLO message to its one-hop neighbours, with its CCID, MN unique code Identifier (MCID) and LC. Each MN updates its LT of neighbours when it receives a HELLO message.

Based on the LT, the source is able to estimate the locomotion of the neighbours (the future position of its neighbours as **a", b", c", d", e", f".** The source selects the neighbour as the next hop, such that the future position of the next hop is closer to the estimated future position of the destination (**D"**). In Figure 31, the next hop of the source node is node **c"** and backup route will be **b"**.

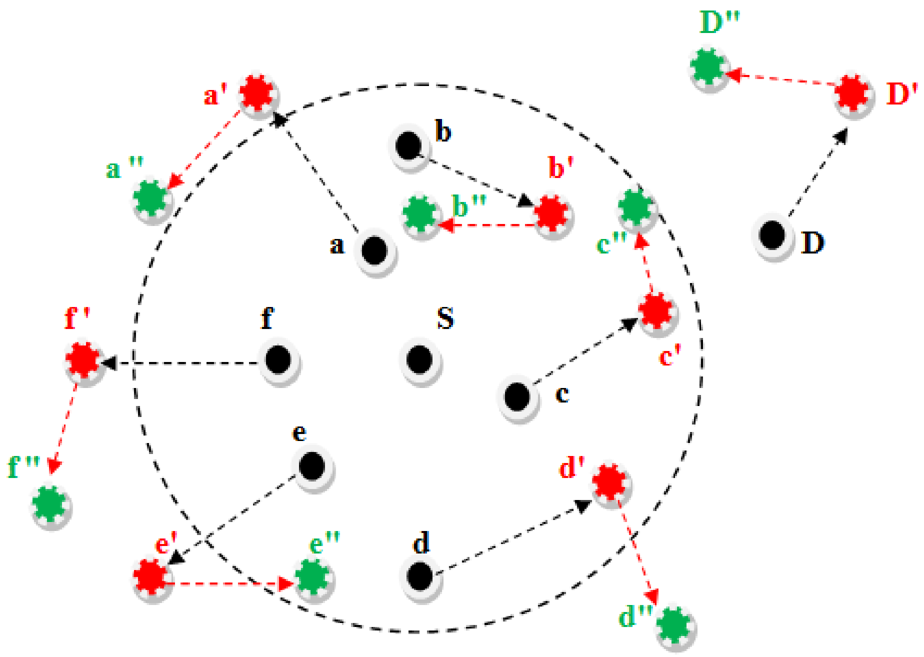


Figure 32. LANDY Locomotion Predication

6.7. Mobile Nodes Distribution and Neighbours Discovery

LANDY localizes routing information distribution in the one-hop range. Thus LANDY will reduce the control overhead, simplify routing computation and save memory storage. Each MN in the network needs to maintain the local status of its MNs neighbours only. For each connection, a MN gets order of **Ni** query packets.

The number of neighbour MNs (**Ni**) may increase or decrease based on the movement of MNs within the local region (CCID). Therefore, the distribution of the MNs within a region for the network state is **S(n)** in the worst case scenario.

In LANDY, the MN updates its LC through position service (e.g. GPS). The MN broadcasts its MCID, CCID and LC in a HELLO message. Data packets are marked with the LC of the sender and the destination, so that the receiving nodes are able to update the neighbour's locomotion information upon receiving the data packet. The MN does not flood the HELLO message. Thus, the LANDY routing protocol reduces the control overhead and simplifies the routing computation.

The HELLO message broadcasting mechanism makes all nodes aware of their neighbours' locomotion information. Each MN broadcasts a HELLO message to its one-hop neighbours, with its MCID, CCID and LC. The HELLO message inter-arrival time is jittered with a uniform distribution to avoid synchronization of neighbours' HELLO messages that could result in conflict. Each MN updates its LT of neighbours when it receives a HELLO message. The LT associates an expiration value with each entry.

If the node does not receive a HELLO message from a neighbour within the expiration time, it removes the neighbour from the table. Based on the LT, the source is able to estimate the future position of its neighbours. Figure 31, illustrates the one-hop broadcasting of the LANDY protocol. At time **t**, the MN **a** broadcasts a HELLO message, encapsulating the LC in the message.

The MNs, **S, a, c** are **b**'s one-hop neighbours. Upon receiving the HELLO message from node **b**, the receiving node updates LT of its neighbour's locomotion information. Since the inter-arrival time of HELLO message $\mathbf{t_i}$ is jittered with a uniform distribution, each node has a different inter-arrival time of HELLO message. At time $\mathbf{t+t_i}$**,** node a broadcasts a new HELLO message with updated LC. The MN **S, c** receive the new HELLO message and updates the LT.

Upon not receiving a HELLO message from a neighbour for a long time (**t2**), the MN assumes that the link to the neighbour is broken and removes the neighbour from the LT. Besides the one-hop HELLO message broadcasting, the MNs will send out the LC in the data packets. The data packet LC transmission provides an alternative to the locomotion distribution. It is helpful in a dense mobile network with heavy traffic load. The mobility of the node at time **t2** is calculated using equation (7):

$$M = \frac{1}{(t2 - t1)} \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2} \tag{7}$$

6.8. Communication Process and Location Calculation between Two Active Mobile Nodes

The MN at the route request stage will send, at least, query packets, but the backtrack packets process might have an impact which results in sending more than **Q** number of query packets. Therefore, the communication packet overhead for the searching stage is **Q(uv'+bp).** This query number depends on the locomotion of MNs.

The route reply stage will send acknowledgements with the chosen path of length **l**. Therefore in normal circumstances, i.e. if there are no dynamic transformations in the network layout between route request and reply stages, the packet overhead for the reply stage is **Q(l)** or **Q(n).** Therefore the packet overhead for LANDY algorithm is **Q(uv'+n(CCID)+bp) = Q(uv'+bp).**

Communication between two active nodes can be initiated as follows:

1) Two MNs moving in their particular self-directed modes come within the range of each other and start communication.

2) A mobile node becomes active at any given time at a random place, and it happens to be in the range of communication of another mobile node.

These initial conditions of active communication, will have an impact on the calculation of the link/path metrics of the MANET. The key factor in the mobility model that is inherent for each mobile node of the MANET, plays the key role in controlling the performance metrics, including link/path metrics.

Two nodes are neighbours if their intermediate distance is less or equal to their transmission range. We assume that all nodes maintain the same radio range, and data rate is constant throughout the network. The distance between two nodes**(x1, y1)** and **(x0, y0)** can be derived from equation (8).

$$d = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2} \tag{8}$$

In LANDY, it is important to know when the link is disconnected with surrounding nodes, for calculating node mobility. Each node can find its location information using GPS, so that it can calculate the node mobility using equations (9) and (10).

$$x_1 = x_0 + \left(v * (\cos\theta)\right) \tag{9}$$

$$y_1 = y_0 + \left(v * (\sin\theta)\right) \tag{10}$$

A node`s velocity is in **sec** unit, and its next location can be calculated. For calculating the next location, it uses current location **p0(x0, y0),** Velocity **v**, Direction Value **θ,** and circular functions formula to derive the next location **p1(x1, y1).** After calculating the next location, its current location, next location and transmission range are added into LT and delivered to the surrounding nodes.

6.9. Right Hand Rule

To route the packet around the local minimum, we utilise the right-hand rule (RHR) to traverse the graph. RHR is one intuitive way to resolve the local minimum problem by following a perimeter of the void region. RHR states that when arriving at node **x** from node **y**, the next edge traversed is the next one sequentially counter-clockwise about **x** form edge (**x,y**).

Figure 33 shows an example of right-hand rule. If the packet from node **S** to node **D** enters into local minimum at node **S**, the packet will first forward to node **A**. If the local minimum is at node **A**, the packet will forward to node **B**.

By implementing the RHR, eventually the packet must get to a node that is closer to the destination, or must return to the starting node in any network connectivity graph. But there are two problems with the RHR in ad hoc networks;

- It may miss a perimeter path in a specific network graph (Figure 34 – a); The packet from **'S'** gets stuck at **'A'** because there is no neighbour that is closer to the destination '**D'**. Then, '**A**' initiates the RHR recovery algorithm to follow '**A**' perimeter path. The RHR selects '**B'** because it is the first node counter clockwise from the line connecting '**A** and **D**'. As a result, the packet follows a loop path '**A , C , E , C , S , H , A**' and fails to find the perimeter path **'A , B , F , G , D'**.
- RHR may follow a degenerate path (Figure 34 – b); The desired perimeter path is '**A, B , E , F , G , H , D** ', but the RHR leads the packet to a much longer path '**A , B , E , F , C , E , B , C , F , G , H , D'**. In certain network topologies, the packet may travel all around the network before getting to the destination.

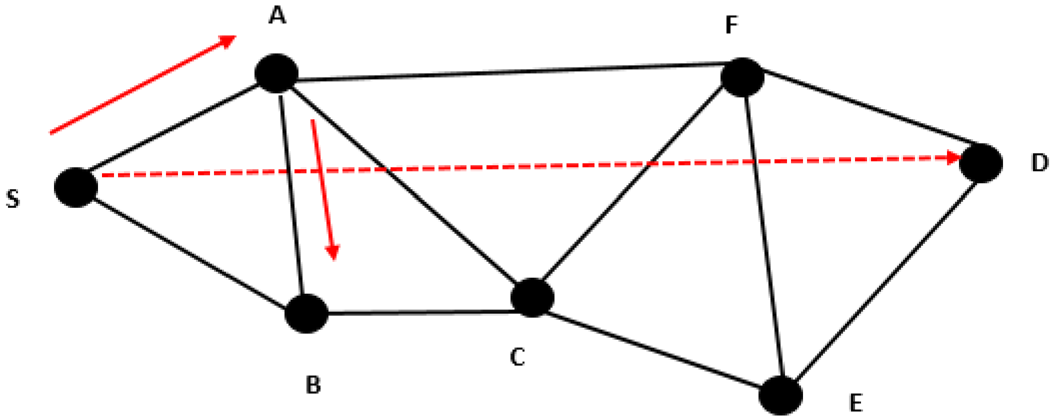
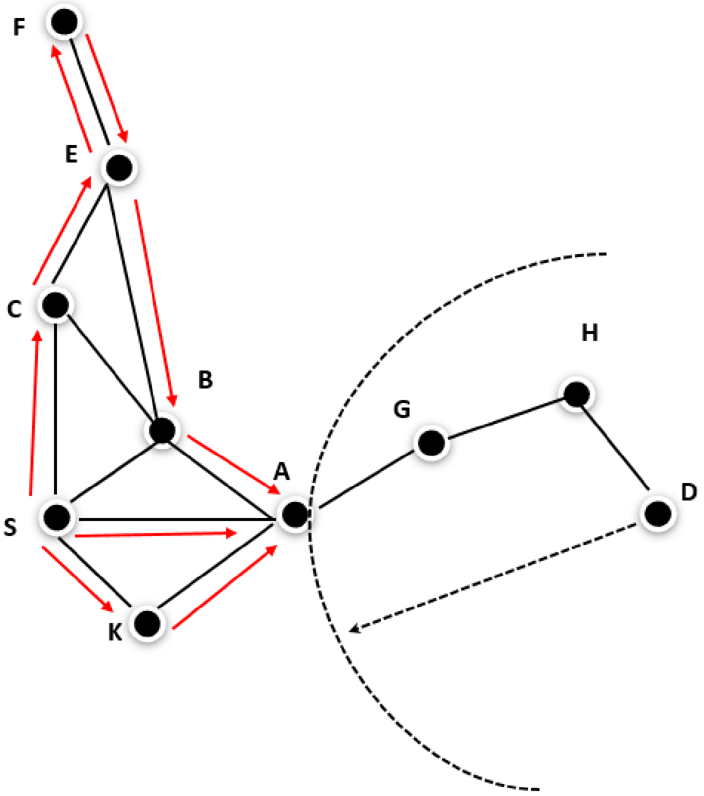
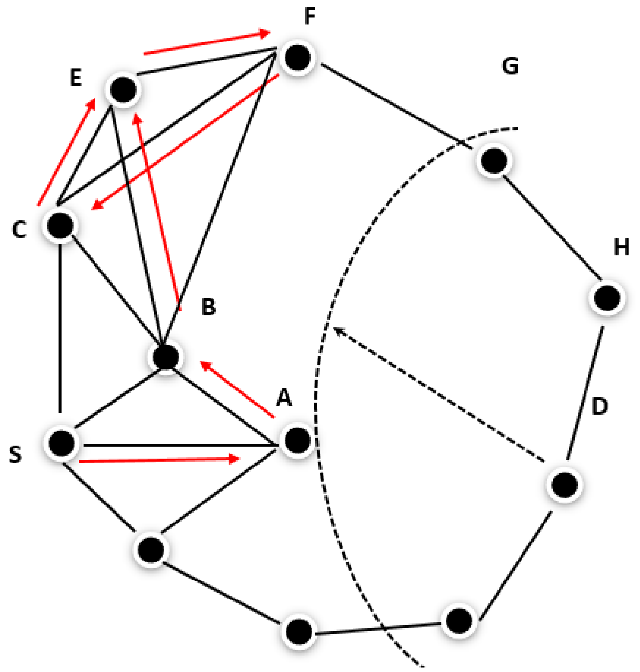


Figure 33. Right Hand Rule



(a) Path missing



(b) Degenerate paths

Figure 34. Right Hand Rule Failures

We present a new algorithm (LAWAND – RHR) that addresses these two issues, and always follows a proper perimeter when given the exact position of nodes. Using simple geometric forms, we prove the new technique finds the shortest perimeter of an obstacle in the network.

In our approach, we assume that each node knows the position of itself and its one-hop neighbours. A node has bidirectional communication links with all of the neighbours within the transmission range (**Tr**). The boundary route of an obstacle is a closed polygon. The edges are not longer than **Tr**, and distance between two vertices which are not neighbouring more than **Tr**. If we consider the above closed polygon, then it is a triangle with internal angles (**IA**) of 60◦.

To achieve the shortest boundary path of an obstacle in a closed polygon that has more than three vertices, the **IA** must be greater than 60◦, otherwise it cannot be the shortest boundary path, as we can link the two neighbouring vertices with an edge that is less than **Tr**.

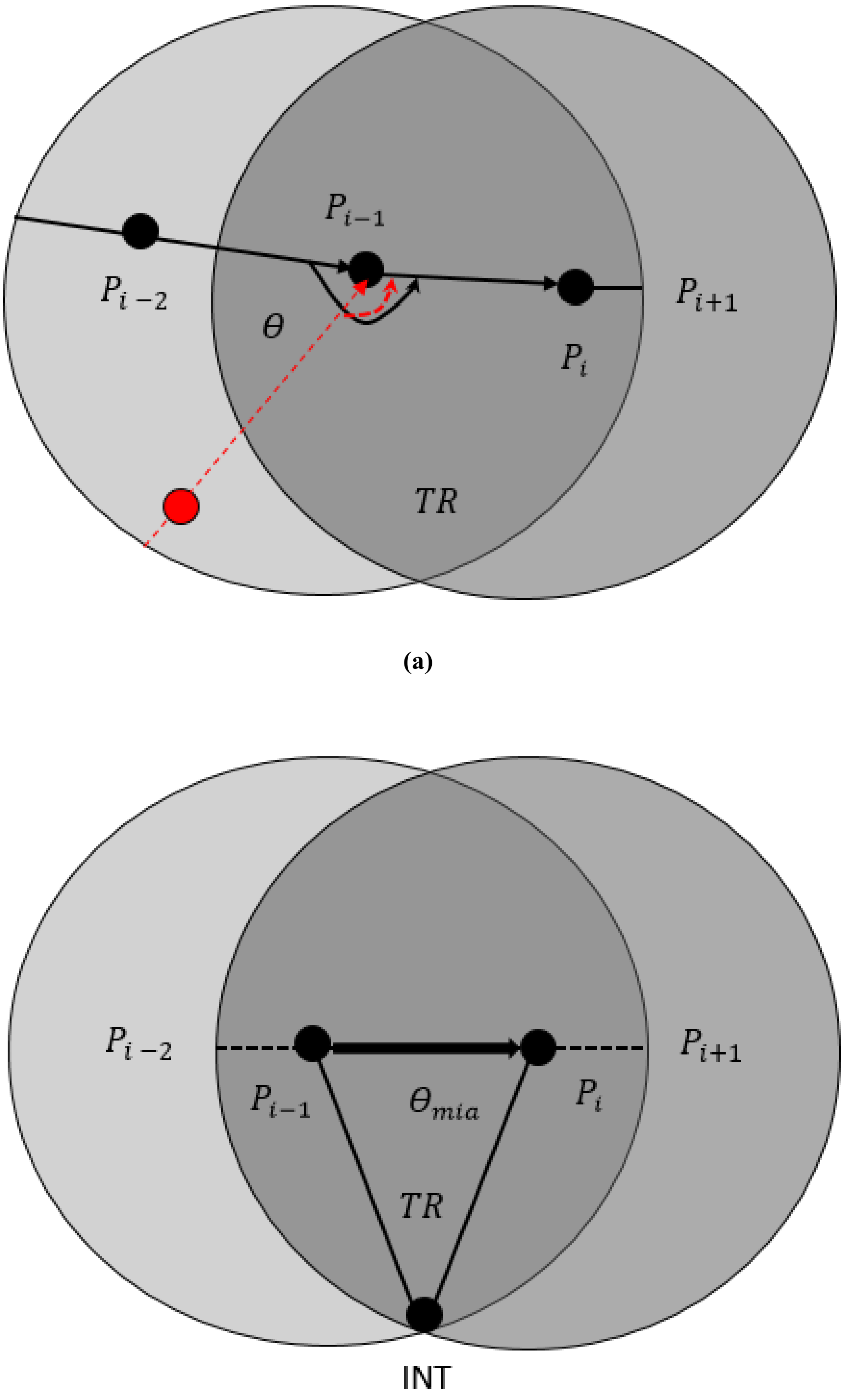
Therefore, the minimal **IA** (**MIA**) must be greater than 60◦, in order to achieve the shortest boundary path for a closed polygon whose edges are **Tr**. The MIA may be greater than 60◦ depending on the distance between the nodes across the entire route.

By fulfilling the above requirements at each node, we can address the crossing edge problem with the right hand rule. In Figure 35 –a, given two points **Pi** and **Pi−1**, the MIA at **Pi** is equal to **∠Pi−1PiINT** (or **∠PiPi−1INT**), where INT is the intersection point of two circles with radius **TR** and centres at **Pi** and **Pi−1** respectively. The MIA **θm** is computed as in (11).

$$\theta_{mia} = \cos - 1\left(P_i P_{i-1} - \tfrac{1}{2} TR\right) \tag{11}$$

In Figure 35 - b, **Pi** receives a packet from **Pi−1** by applying RHR, assuming no crossing edges during the journey. **Pi−2** must be located in the shaded region **Ri−2**, where **Pi−2** can reach **Pi−1. Pi−2** cannot be located in the transit region (**TR**) because, if it were located in the region, Pi would be the next node instead of **Pi−1**.

Therefore, **Pi+1** must be located in **Ri+1** region. As a result, the **IA θ** is greater than the MIA **(θmia),** and link **PiPi+1** crosses neither **Pi−2Pi−1** nor **Pi−1Pi**.



(a)

(b)

Figure 35. LAWAND Algorithm - Minimal Internal Angle

Nodes in the 'Establish Region' (ER) are not identified at either **Pi** or **Pi+1**, and nodes in the transit region cannot be elected when **Pi** implementing the RHR to forward the packet. Therefore, if there are two nodes in the transit and establish region respectively, and they are directly connected, the RHR will miss the path.

To address this issue, the packet must visit a node in the transit region, and confirm if the node is linked to any node in the 'Establish Region'.

The 'Establish Region' is an area where a node may have a path that crosses line **PiPi+1**, and the transit region is an area where a node is likely to have a path to a node in the 'Establish Region'.

In order not to miss the path, the packet must be forwarded to the node in the transit region even if the node is not on the shortest boundary path. Figure 36 graphically defines the transit region and the establish region.

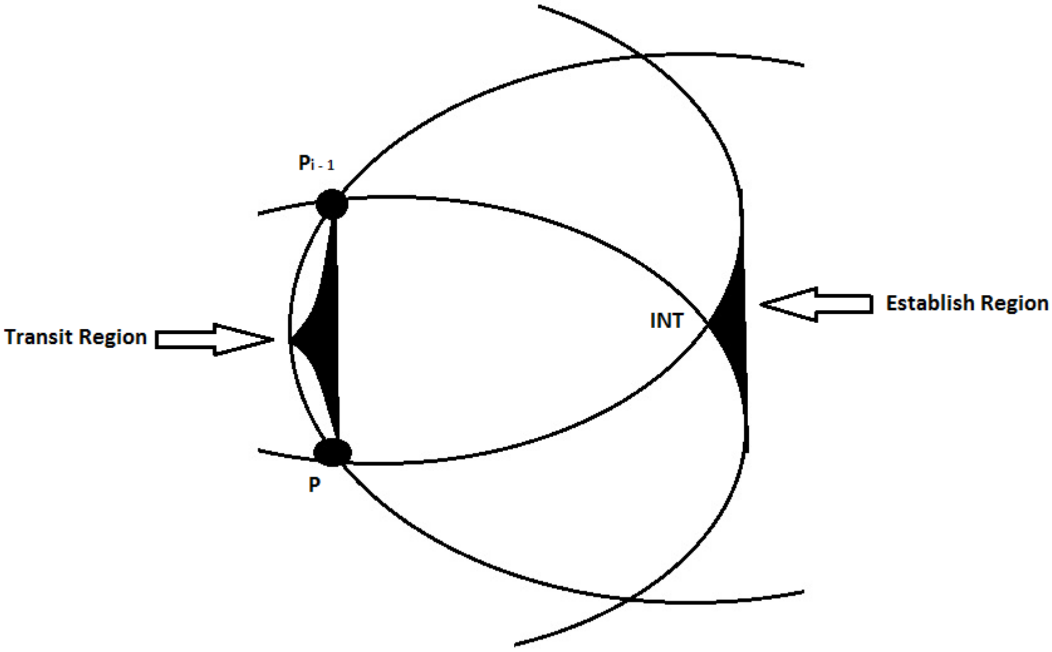


Figure 36. LAWAND Algorithm - Transit Region and Establish Region

Figure 37, shows the pseudocode for the new algorithm. In this routing scheme, the packet must remember the first two nodes on the boundary path in order to avoid travelling the obstacle forever.

This will result in a slightly longer boundary path of the obstacle than the shorter one. On the other hand, it always finds a path between the nodes if one exists, as it scans the whole area within TR from the boundary.

Algorithm 1: LAWAND - RHR

***Data**: **Ns**: Neighbour nodes, **Xi**: Current node, **Xi – 1**: Previous node, **Tr**: Transmission radius*

***Result**: **Xi + 1**: Next node*

```
$\theta_{mia} = \cos^{-1}(P_i\,P_{i-1}/2Tr)$
  $P_{i+1} = \text{NNNC}\,(P_i\,, P_{i-1}\,, N_s)$
    $\boldsymbol{while}\ 0 < \angle\, P_{i-1}\,P_i\,P_{i+1} \le \theta_{mia}$ do
      $N_s = N_S - N_{i+1}$
      $P_{i+1} = \text{NNNC}\,(P_i, P_{i+1}, N_s)$
    $end$
  $N_{s,v} = TR\,(P_i, P_{i+1}, N_s)$
    $\boldsymbol{while}\ N_{s,v} \neq \emptyset\ \boldsymbol{do}$
        $P_{i+1} = \text{NNNC}\,(P_i, P_{i-1}, N_s)$
        $N_{s,v} = TR\,(P_i, P_{i+1}, N_s)$
    $end$
return $P_{i+1}$
```

Figure 37. LAWAND Algorithm

***Next neighbouring node clockwise** (NNNC) returns the first node counter clockwise about the current node from the line connecting the current and previous node.*

***Transit Region (TR)** returns a node that is located in the transit region*

6.10. LANDY Forwarding Strategy

The MN distributes the locomotion information through one-hop HELLO message broadcasting. Upon receiving the LT from the HELLO message and the data packet, the MN updates the LT. The node will be able to send out a data packet, receive a data packet and forward the packet, if it is not the destination.

The node will choose a one-hop neighbour as the next hop (forwarding node), so that the next hop is closer to the destination in the near future. The packet is forwarded to the next hop Figure 39.

Upon receiving the packet, the receiving node will establish the next hop, based on the same mechanism. This forwarding process is repeated until the destination is reached.

In some situations, the backup path will be utilised if the primary path is not available; using the back track process, nodes can trackback for alternative routes just for the three previous nodes. If the packet is in a 'Local Maximum Problem' Figure 38, then the node will start a recovery process, to navigate the planar graph to the destination. There are three types of packet operations in LANDY:

- HELLO
- Packet sending – Figure 40
- Packet Receiving and Forwarding – Figure 41

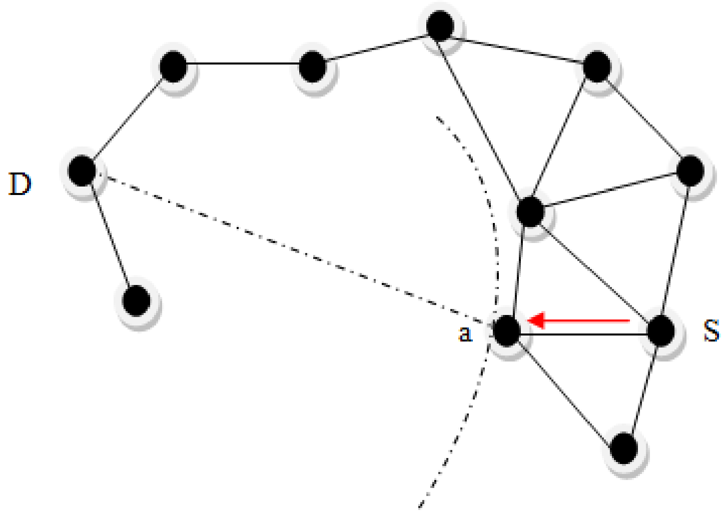


Figure 38. Local Maximum Problem

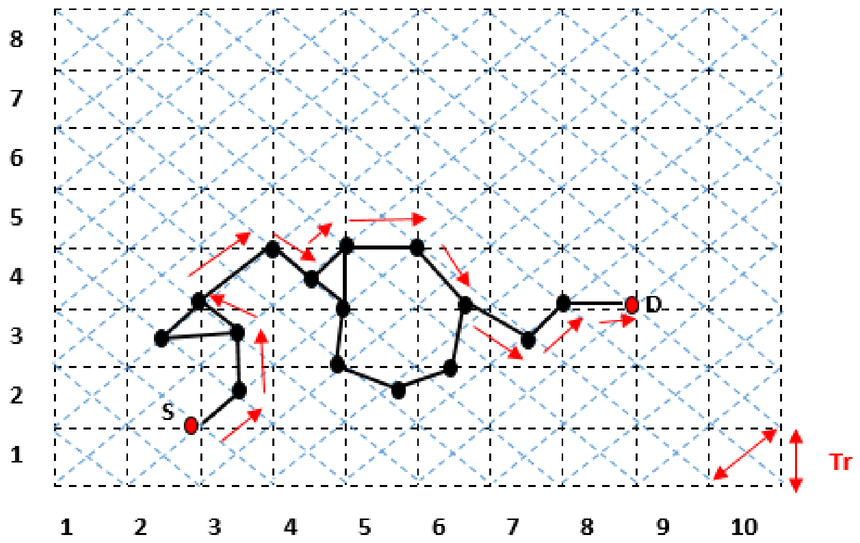


Figure 39. Packet Forwarding

6.10.1. HELLO

LANDY uses HELLO packets to discover and maintain neighbour relationships.

6.10.2. Packet Sending

Once there is a packet in the outgoing queue of a mobile node, the mobile node first queries the location service to get the destination's LC. Based upon the LT, the mobile node is able to determine the next hop.

If the mobile node finds out a local minimum, it will utilise the back track process to find an alternate path, otherwise it will enter into the recovery mode to traverse the planar graph to the destination. If the mobile node cannot find a next hop which is closer to the destination in the near future, the mobile node will retransmit the packet in the next time slot.

If the number of retransmission is greater than a threshold, the packet will be dropped. The retransmission mechanism is implemented in the MAC, and it is supported by most of the standard MAC protocols. Figure 40 shows the pseudo code of packet sending.

6.10.3. Packet Receiving and Forwarding

Upon receiving a packet, the mobile node will first check whether the packet's destination is itself, and if it is, it will pass the data payload to the high layer. If it is not the destination, the mobile node will forward the packet to the optimal forwarding node, based upon the forwarding strategy.

If it is in a local minimum, the mobile node will utilise the back track process to find an alternate path, otherwise it will enter into recovery mode to traverse the planar graph to the destination.

If the mobile node finds out a packet, marked with recovery mode can be recovered, the mobile node will forward the packet based upon the forwarding strategy. There is a time to live (TTL) timer in every packet. If the packet is in a loop or the packet traverses a larger number of intermediate nodes, the TTL is zero. The mobile node will drop the packet. Figure 41 shows the pseudo code of packet receiving and forwarding

Algorithm 2: Packet Sending (LC, LT, Future_dst)

Constant: Radio_Range
Data: LC, LT, Packet_Queue, Query Location Service Queue (QLSQ), Next_Hop, Distance, CANDIDATE (CAND), Destination (dst).
Result: Future_dst

```
begin
  While (Packet_Queue! =Ø);
    If ((dst_LC = Look_up (dst, LT) ==Ø))
          Insert (dst, QLSQ);
      If  ((d == distance <= Radio_Range)
          Insert (LC, MCID, CCID);
      Else
          Set mode to GREEDY; Set NEXT_HOP to self;
        Foreach Neighbour
          HOP_CAND = Look_up (LT);
          If (Future_dst (HOP_CAND) < Future_dst(NEXT_HOP))
            NEXT_HOP = HOP_CAND;
          end
          If  (NEXT_HOP  == self);
            Set mode to RECOVERY; Construct (RNG);
            NEXT_HOP = Traverse (RNG, LAWAND-RHR);
          end
        end
      end
    end
  end
end
```

Figure 40. LANDY Pseudo Code of Packet Sending

Algorithm 3: Packet Receiving and Forwarding (LC, LT)

Constant: Radio_Range
Data: LC, LT, Packet_Queue, Query Location Service Queue (QLSQ), Next_Hop, Distance, CANDIDATE (CAND), Destination (dst).
Result: Future_dst

```
begin
  While (Packet_Forward_Queue != Ø) {
    If (mode == GREEDY) {
      If ((dst_LC = Look_up (dst, LT) == Ø))
            Insert (dst, QLSQ);
        If { ((d == distance <= Radio_Range)
              Insert (LC, MCID, CCID); }
        Else {
              Set NEXT_HOP to self;
          Foreach Neighbour {
                HOP_ CAND = Look_up(LT);
            If (Future_dst (HOP_CAND) < Future_dst(NEXT_HOP))
                NEXT_HOP =  HOP_CAND;
            end
            If (NEXT_HOP  == self){
                Set mode to RECOVERY; Construct (RNG);
                NEXT_HOP = Traverse (RNG, LAWAND-RHR);
            end
          end
        end
      end
      If (mode == RECOVERY) {
        If ((dst_LC = Look_up (dst, LT) == Ø))
              Insert (dst, QLSQ);
          If (RECOVER (packet) == TRUE){ Set mode to GREEDY;
            Foreach Neighbour {
                  HOP_ CAND = Look_up (LT);
              If (Future_dst (HOP_ CAND) < Future_dst(NEXT_HOP))
                  NEXT_HOP =  HOP_ CAND;
              end
            end
          Else {
                Set mode to RECOVERY; Construct (RNG);
                NEXT_HOP = Traverse (RNG, LAWAND-RHR);
          end
        end
      end
    end
  end
end
```

Figure 41. LANDY Pseudo Code of Packet Receiving and Forwarding

6.11. Locomotion Components

There are two types of packets in LANDY: (1) HELLO message packets (2) data packets. The content of the HELLO message is LC of the transmitting node. The MNs distribute the locomotion information through LC as shown on Table 16. Upon receiving the LC of the neighbours, the MN is able to construct the LT and route the packet.

Table 16. Locomotion Components Format

Field	Description
CCID	Cell unique code Identifier
MCID	Mobile Node unique code Identifier
P1	Position of first sample
P2	Position of second sample
P3	Position of third sample
T1	Time stamp of first sample
T2	Time stamp of second sample
T3	Time stamp of third sample
Θ	Moving direction
V	velocity

6.12. The Data Packet Header

The data packet consists of a data packet header and the data payload. LANDY data packet header is a modified version of the GPSR packet header. The data packet header provides:

(1) LC distribution.

(2) Information in the recovery mode.

Two types of packet mode are defined in LANDY: ‘Forwarding mode and Recovery mode’. The Forwarding mode is the mode in which the packet is forwarded by LANDY forwarding algorithm.

The Recovery mode is the mode in which the packet enters into a local maximum problem and traverses the planar graph to the destination. The data packet header format is shown in Table 17.

Table 17. Data Packet Format

Field	Description
P_M	Packet mode
H_C	Hope count
LC_D	Locomotion components of the destination
LC_BP	Locomotion components of the node where packet entered back track process
LC_C	Locomotion components of the node where packet entered recovery mode
LC_P	Locomotion components of the pervious node
C_ID	Cell unique code Identifier
P_F	Position of point the packet entered the current face
L_T	Life time
F_F	First edge traversed on the current face
L_F	Last edge traversed on the current face

6.13. Cell-Based Forwarding

In the event of location based service not being available, and when the cell coordinates of neighbour nodes are available instead of the position of the nodes, we can forward the packet based on the cells ID (Cell unique code Identifier).

In this cell-based forwarding, the packet is forwarded to a neighbour cell that is closer to the destination cell than the current cell; the packet is supposed to contain the destination cell, and the current node has a list of neighbour cells that are reachable.

For the distance between two cells, we calculate the Euclidean distance between two centres of the cells using (12).

$$Cell_{x_1y_1}Cell_{x_2y_2} = \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2} * d \qquad (12)$$

Where $\boldsymbol{d}$ *is the distance to gateway.* $\boldsymbol{Cell_{x_1y_1}Cell_{x_2y_2}}$ *, are cell coordinates.*

The procedure to decide the next cell is shown in Figure 42. After determining the next cell, the current node chooses the next forwarding node that leads the packet to the selected cell.

The shortest path is chosen. If there are still multiple candidates, in this work, we choose the latest updated path for reliability. Note that not all of the nodes in a cell can communicate directly with nodes in an adjacent cell.

Therefore, transferring packets between adjacent cells may require forwarding packets between nodes in the same cell. Note that position based forwarding is likely to choose a distant neighbour to reduce the path length, but the distant node is more likely to move out of the radio range. Generally, the reliability of the radio link is inversely proportional to the square of the distance.

Algorithm 4*:* CellBasedForwarding (CurrentCellCCID, DestinationCellCCID)

Data: CurrentCellCCID, Coordinates of the CurrentCell, DestinationCellCCID, Coordinates of the DestinationCell

Result: NextCellCCID, Coordinates of the next cell Dis

```
DisSelf =CellDistance (CurrentCellCCID, DestinationCellCCID)
DisBest = DisSelf
for each NeighbourCell do
    DisNeighbour =CellDistance (NeighbourCell, DestinationCellCCID)
    if DisNeighbour < DisBest then
        DisBest = DisNeighbour
        NextCellCCID = NeighbourCell
    end
end
if DisBest == DisSelf then
    return CCIDFailure
else
    return NextCellCCID
end
```

Figure 42. LANDY Pseudo Code of Cell Based Forwarding

6.14. Backtracking Concept and Time

LANDY backtracking concept on blocked routes: Packets can backtrack to the previous node (up to three previous nodes) to get re-routed along a different valid path. Nodes that receive the backtrack packet calculate the next closest neighbour node to the destination and send it along the new path.

If no alternate route is available, then the packet, is in a ‘Local Maximum’. Then the MN will start the inherent recovery mechanism, to navigate the planar graph to the destination.

If a MN gets a query packet and this is checked against the queue packets stored in the LT, whose size is of order **bp** and **LC** for a local region, to check whether, the arrived query packet contains a loop or not, then each MN gets set of **Ni** query packets.

Therefore, the time intricacy of processing query packets is **tq (LT.Ni).** If a node gets a backtrack packet, then it will send another query on that link, if one exists. Therefore the time intricacy is **tq (LT.Ni+LT),** which is equal to **tq (LT.Ni)** in the local region which CCID is known equation (13).

$$t_q(LT.Ni + LT) = t_q(LT.Ni) \tag{13}$$

6.15. Failure Detection and Recovery Process

The failure detection recovery initiation process is simple: Active nodes monitor their signal quality and defined bandwidth threshold. It is assumes a bidirectional connection, which allows the node to initiate the recovery as soon as it detects a failure. LANDY employs perimeter routing as a recovery mechanism, such as used in GPSR [5, 17].

The perimeter routing is a graph with no intersecting edges. The RNG has been used in LANDY`s recovery algorithm, which can be defined as a graph in which an edge **(u, v)** exists between vertices **u** and **v** if the distance **||uv||** is less than or equal to the distance between every other vertex **w**.

There are two modes of packet forwarding in LANDY: ‘Forwarding mode and Recovery mode’. A packet enters the recovery mode when the protocol determines that it has arrived at a ‘Local Maximum’. It returns to greedy mode when it reaches a node with an estimated location, closer to the destination than the node where the packet entered the perimeter mode.

To support both forwarding mode and recovery mode, a MN will construct the RNG of neighbours when it enters recovery mode, as well as updating the LT when it receives HELLO packets.

Upon receiving a forwarding mode packet for forwarding, a MN searches its LT for the neighbour closest to the packet’s destination in the near future. If this neighbour is closer to the destination than the mobile node itself, the node selects the neighbour as the next hop of the packet and forwards the packet to the next hop. When no neighbour is closer, the node marks the packet into the recovery mode. LANDY forwards the packet on progressively closer faces of the planar graph RNG to the destination, using the right-hand rule.

When a packet enters the recovery mode, LANDY records the position where the packet enters the recovery mode. This is used for the downstream hops to determine whether to recover from the recovery mode. At the first traverse of recovery mode, the MN forwards the packet to the adjacent edge based on the right hand rule. When LANDY forwards a packet onto a new face, it records the position on line **SD** (**S** is the source where the packet enters the recovery mode and **D** is the destination) shared between the previous and new faces, and the first edge on the traversed face, in the packet header.

Upon receiving a recovery mode packet, LANDY first determines whether it is the packet's destination. If so, LANDY passes the 'Packet Data Payload' (PDU) to the higher layer. If it is not the packet destination, LANDY then determines whether the packet can be recovered from the recovery mode.

LANDY compares its LC and the position where the packet entered into the recovery mode. If the distance from the node to the destination in the near future is less than the distance from the recovery entering position to the destination, LANDY returns the packet mode back to the forwarding mode.

Otherwise, the node traverses the planar graph. LANDY forwards the packet along the face intersected by the line **SD** using the right-hand rule. When the destination is not reachable (i.e., it is disconnected from the graph), LANDY will traverse the disconnected face entirely and enter the first edge of that face twice.

LANDY determines that it is a disconnected face, and drops the packet to the disconnected destination. This will prevent packet routing loop. The recovery process repeats at successively closer faces to the destination. Eventually, the face containing the destination is reached, as long as the planar graph is connected. Recovery with LANDY is much faster than with other location protocols which use mainly greedy algorithms (such as GPRS), as no signalling or configuration of the intermediate nodes is required after a failure.

The key difference is that it allows sharing of locomotion and velocity information among the nodes through LT. A node may also be both an end node (Source or/ and destination). In this case, it will switch to recovery mode until it finds a neighbour, and after the connection is recovered, the configuration is fixed, preventing possible reconfiguration and signal collision, in the event of additional failures.

6.16. Chapter Summary

In this chapter we have reviewed in depth design and each of the process of the proposed lightweight position based routing protocol LANDY. Also, we have explained how LANDY uses a localized routing technique which combines a unique locomotion prediction method and velocity information of MNs to route packets.

LANDY uses no periodic control packet network wide floods, or periodic neighbour sensing, and adapts its behaviour based on network conditions and application sending pattern, allowing efficient detection of broken links and expiration of routing state that is no longer needed.

The protocol is capable of optimising routing performance in advanced mobility scenarios, by reducing the control overhead and improving the data packet delivery.

In addition, the approach of using locomotion prediction, has the advantage of fast and accurate routing over other position based routing algorithms in mobile scenarios.

Recovery with LANDY is faster than other location protocols, which use mainly greedy algorithms, (such as GPRS), no signalling or configuration of the intermediate nodes is required after a failure. The key difference is that it allows sharing of locomotion and velocity information among the nodes through locomotion table.

In this chapter we also explained the process of LAWAND right hand rule algorithm: The LAWAND right hand rule algorithm is developed to address these two issues (right hand rule may miss a perimeter path in a specific network graph, and right hand rule may follow a degenerate path) and always follows a proper perimeter when given the exact position of nodes. Using simple geometric forms we prove the new technique finds the shortest perimeter of an obstacle in the network. In the next chapter we will explain in details the implementation and the modelling of LANDY routing protocol in OPNET.

CHAPTER 7. LANDY PROTOCOL MODELING AND EVALUATION

In this chapter, we present the implementation details of LANDY routing protocol, and the LANDY model in OPNET. We implement LANDY routing protocol in OPNET v 14.5. In addition, we introduce a new measurement method called: Probability of Communication Process. This method is used to measure the success rate of an established path by a MANET routing protocol.

It allows stress testing and inspection of the stability, scalability and adaptability of MANET routing protocols. We analysed the effect of 'route and link connectivity' on the performance of protocols under two different mobility models. Results show the evaluation and performance of the proposed protocol, under a unified simulation environment for different scenarios.

7.1. LANDY Routing Protocol Implementation

As discussed in the previous chapter, each LANDY mobile node receives position information through GPS and updates its own LT. It then broadcasts the LT in the HELLO message to the neighbours. The inter-arrival time of HELLO message is in a uniformed distribution [**0.5B, 1.5B**], with means of **B** to avoid synchronization of HELLO message. **B** is **5 sec**, typically.

Upon receiving a HELLO message from a neighbour, a mobile node updates its neighbour LT. An LC entry has an expiration time associated which it sets to **T = 3B**, two times the maximum jittered HELLO message interval, typically.

When a mobile node has a packet to send, the node first gets the destination's LC, by using location service.

The mobile node marks the packet with the destination's LC after querying location service. Based on the neighbour LT, the mobile node employs the greedy routing to perform packet forwarding. The estimated future position is the node position at time of **t+B** (current time + mean of the HELLO message inter-arrival time).

The packet is forwarded to the next hop. Upon receiving the packet, the next hop will repeat the function. The packet is transmitted in this regime until it reaches the destination. If the mobile node finds no neighbour's future position is closer to the destination than itself, the forwarding strategy utilises the back track process and enters into recovery mode.

The mobile node constructs a RNG based on the neighbour LT, and traverses its face according to the right hand rule. Upon receiving a recovery mode packet, the mobile node first checks its own LC.

The protocol returns to greedy mode if the distance from its future position to the destination's future position, is less than that from the location at which the packet entered into the recovery mode. Otherwise, LANDY continues perimeter routing. The accuracy of perimeter routing depends on the network planarization. To keep the RNG planarization up-to-date, the RNG is reconstructed every time the mobile node performs the perimeter routing.

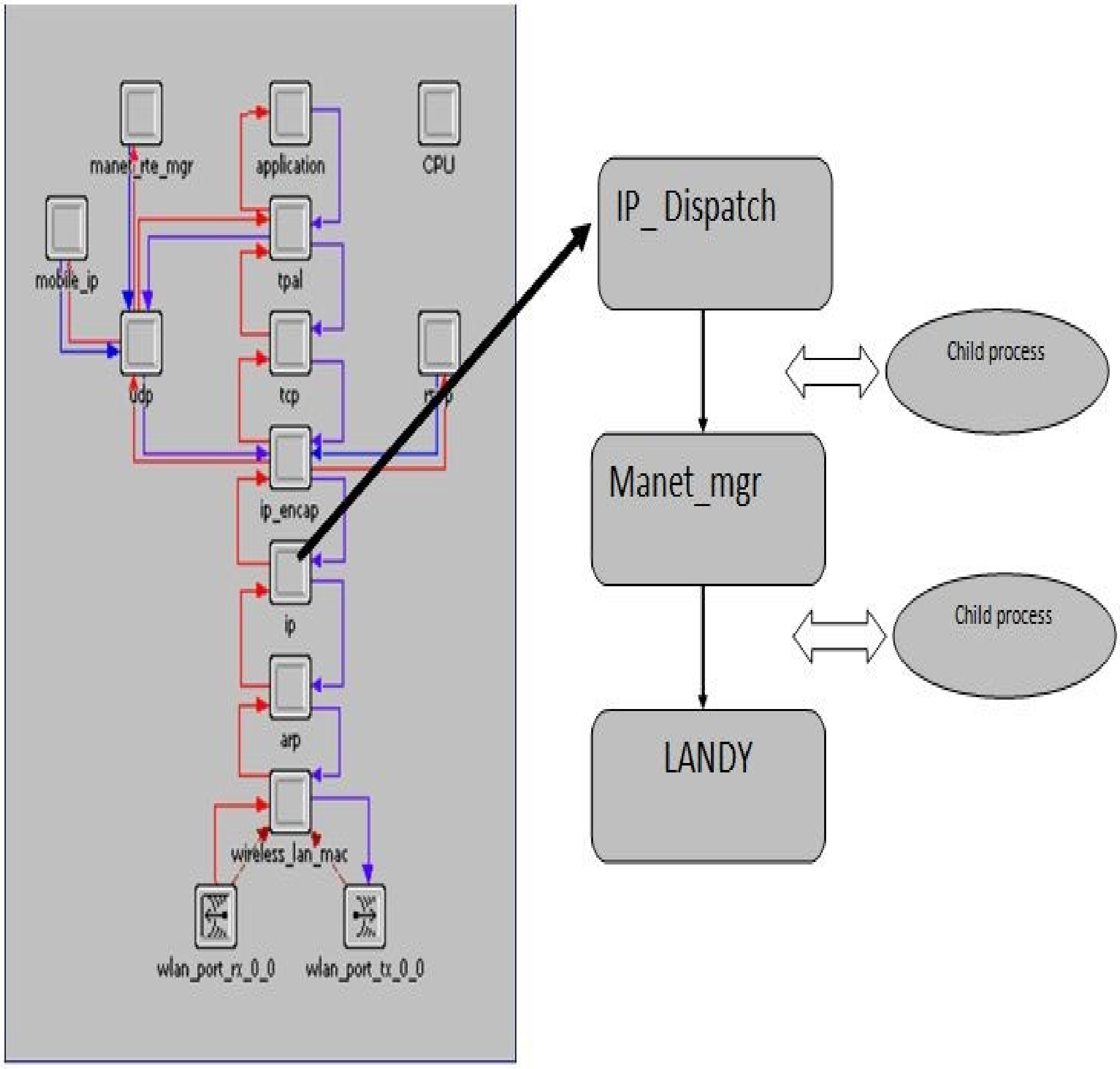


Figure 43. Model Architecture

7.2. LANDY Model

The LANDY protocol is implemented in the OPNET as a process model Table 18 in wireless MNs. The LANDY process model can be represented in a STD. The STD process editor is used to develop process models which control module behaviour. It uses finite state machine approach to support specification at any level of detail, of protocol, resources, applications, algorithms and queuing policies. State and transitions graphically defines the progression of a process in response to events.

Figure 44 shows the LANDY STD. The twelve states are used to initialise the state variables, and set up communication with the adjacent layers.

Table 18. LANDY Process Model

State	Proses
INIT	The 'init' state executes state initialization.
WAIT	The 'wait' state waits for the lower layer to finalize the address resolution.
DISCOVER	The 'discover' state indicates the completion of lower layer initialization.
WAIT_2	The 'wait_2'state waits for all nodes to finish initialization.
DISPATCH	The 'dispatch' state is an idle state, which wait for interrupts.
REGISTER	The 'Register' state handles packet receiving and updating LC and LT.
BROADCAST	The 'broadcast' state broadcasts a HELLO message. The LT is encapsulated in the HELLO message.
WAIT_3	The 'wait_3'state waits for all nodes to finish initialization.
DISCOVER_1	The 'discover_1' state indicates the completion of lower layer initialization.
FORWARD	The 'forward' state handles packet forwarding.
GENERATE	The 'generate' state generates a data packet.
RECEIVE	The 'receive' state handles packet receiving.

If the received packet is HELLO message, the node will update LT. If the received packet is a date packet, the node will decide whether it is the packet destination. If it is, the mobile node will process the data packet and update the statistics. Otherwise, the mobile node will call packet forwarding function to forward the packet to the next hop.

The ‘LT timeout’ state updates LT. Seven types of interrupt are provided in the process model:

(1) REGISTER; (2) BROADCAST; (3) DISCOVER; (4) LTISTTIMEOUT; (5) STREAM_INTERRUPT; (6) GENERATE; (7) RECEIVE AND FORWARD

The REGISTER interrupt is to update LC and LT. The BROADCAST is to trigger broadcasting HELLO message. If a BROADCAST interrupt is received, the ‘dispatch’ state will transit to ‘broadcast’. After broadcast executions, the ‘broadcast’ state will return to ‘dispatch’. If receiving a GENERATE interrupt, the ‘dispatch’ state will transit to ‘generate’. After generating a data packet, the ‘generate’ state will return to ‘dispatch’ and wait for further interrupts. If receiving a ‘LTISTTIMEOUT’ interrupt, the ‘dispatch’ state transits to ‘LTtimeout’ state. After ‘LTtimout’ executions, the ‘LTtimeout’ state will return to ‘dispatch’ state. If receiving a STREAM_INTERRUPT interrupt, the ‘dispatch’ state transits to ‘receive’ state. After packet processing, the ‘receive’ state will return to ‘dispatch’ state.

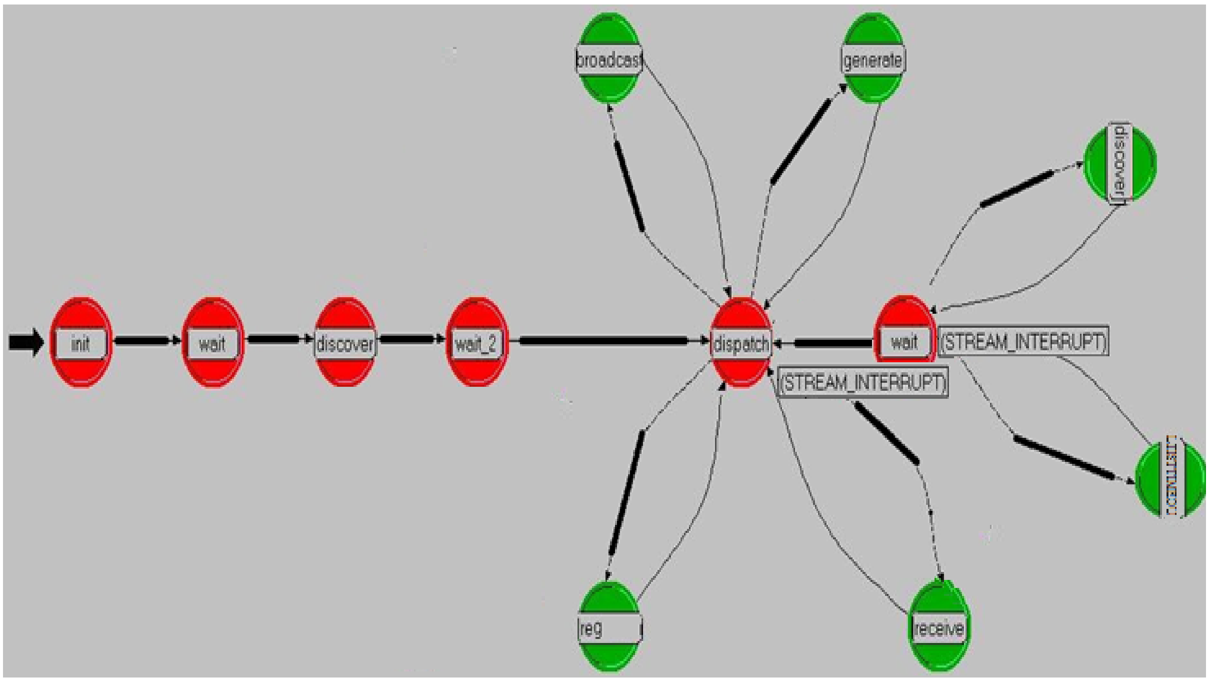


Figure 44. LANDY STD

Table 19. Major Functions of LANDY Process Model

Code	function
SV	LC_sv_init (void); // State initialization
SV	LC_sent_stats_update (double pkt_size); // Update statistics
SV	LC_received_stats_update (double pkt_size); // Update statistics
SV	LC_packet_flow_info_read (void); // read data flow info
SV	LC_packet_receive(void); // handle packet receiving
SV	LC_forward_packet (void); // forward data packet
SV	LC_bp_packet (void); // broadcast HELLO message
SV	LC_bp_destroy (Packet*); // receiving HELLO message
SV	LC_bp_receive (Packet*); // handle packet receive/forward
SV	LC_bp_update(void); // update node location
SV	LC_generate_packet (void); // generate data packet
SV	LC_broadcast_packet (void); // broadcast HELLO message
SV	LC_HELLO _destroy (Packet*); // receiving HELLO message
SV	LC_datapkt_receive (Packet*); // handle packet receive/forward
SV	LC_location_update(void); // update node location
SV	LC_LE_init(void); // initialize LE
SV	LC_parameters_init(void); // LANDY parameters initialization
SV	LC_LT_update(LE* LE_ptr); // update the LT list
SV	LC_LT_timeout(int intrpt_code); // timout the LT list
SV	CELL_generate_packet (void); // generate data packet
SV	CELL_broadcast_packet (void); // broadcast HELLO message
SV	CELL_HELLO _destroy (Packet*); // receiving HELLO message
SV	CELL_datapkt_receive (Packet*); // handle packet receive/forward
SV	CELL_location_update(void); // update Cell location
SO	LC_search_nexthop(Objid dest, LE* LE_ptr); // search the next hop.

SO	CELL_search_nexthop(Objid dest, CCID* CCIM_ptr); // search the next hop.
SD	CELL_dist(CCID*CLP* CLP_ptr1, CCID*CLP* CLP_ptr2); // determine the distance between two CELL.
SD	CELL_dist_future(CCID*CLP* CLP_ptr1, CCID*CLP* CLP_ptr2); // determine the future distance between two CELL.
SC	Cell_intersection_exist(CLP* CLP_ptr1, CLP* CLP_ptr2, CLP* CLP_ptr3, CLP* CLP_ptr4); // determine the intersection
SD	LC_dist(MCID*LP* LP_ptr1, MCID*LP* LP_ptr2); // determine the distance between two nodes.
SD	LC_dist_future(MCID*LP* LP_ptr1, MCID*LP* LP_ptr2); // determine the future distance between two nodes.
SLC	LC_intersection_exist(MCID*LP* LP_ptr1, MCID*LP* LP_ptr2, LP* MCID*LP_ptr3, MCID*LP* LP_ptr4); // determine the intersection
Static Void = SV, Static Object Id = SO, Static Double = SD, Static LC = SLC *Locomotion position = LP, Static Cell = SC, Cell Locomotion position = CLP*	

7.3. Connectivity between Mobile Nodes

Extensive Link connectivity analysis is carried out by [30], which is based on undirected graph theory. However, the research did not consider the route overhead. Based on the work therein, we expand and make improvements to include the route overhead in our analysis and simulation. Also a new metric for measuring routing performance, called ‘Probability of Communication Process’, between active MNs is presented. The measurement is based on the assembled paths over randomised dynamic network topologies using “Sobol sequence” algorithm.

7.3.1. Probability of Link Connectivity between Active Mobile Nodes

A graph is made of number of vertices and edges, where an edge is a link between two vertices. If an individual edge of a graph is linked with some unique value, then the graph is weighted.

The number of edges linked with the vertex is identified as degree of any vertex **v** and is denoted by **d(v).** The minimum degree of a graph is the least degree of a vertex of a graph denoted by **δ(G),** and the maximum degree of a graph is the maximum degree of any vertex of a graph denoted by Δ**(G).** A graph **G** is consistent if **Δ (G) = δ(G).** A graph is connected, if a path exists between two MNs, otherwise, it is disconnected [30].

In connected networks, MNs can communicate with each other via gateway MN or multi links. In disconnected networks, there are several isolated sub-networks, forming a sub-graph of connected MNs, which cannot communicate to other sub-networks.

Minimum node degree (**d**) is a major factor for multi-hop communication. It represent the relation between the node and its neighbour's MNs.

If '**d = 1**'then the network is connected, which mean the node is able communicate with its neighbour, otherwise it is disconnected (isolated) when '**d = 0'**. Equation (14) represents the probability of link connectivity for active MNs, and the minimum node degree of connected network (graph G) is represented in (15) [30],

$$Prob_{(lc>0)} = (1 - e^{-\rho\pi r^2})^n \tag{14}$$

$$d_{\min(G>0)} = min_{\forall u \ni G}\{d(u)\} \tag{15}$$

*where; **Prob**lc is the probability of link connectivity, **ρ** is node density, **r** is node transmission range, and **n** is the number of nodes in the network, **d min (G),** is minimum node degree of connected graph, **u** is the degree of a node, denoted as **d(u),** is the number of neighbour s of node u.*

Additionally, a k-connected theory graph exists, when at least two MNs can communicate via **k** path. The MN, at the route request stage, will send (at least) query packets; But the backtrack packets (**bp**) process might have an impact, which result in sending more than Q number of query packets. Therefore the communication packet overhead for the searching stage is **Q (uv'+bp).** This query number depends on the locomotion of MNs.

The route reply stage will send ACK with the chosen path of length **l**. Therefore in normal circumstances, i.e. if there is no dynamic transformation in the network layout between route request and reply stages, the packet overhead for the reply stage is **Q(l)** or **Q(n).** Therefore, the packet overhead is presented in (16).

$$Q(uv' + n(CCID) + bp) = Q(uv' + bp) \tag{16}$$

Where, ***Q*** *is the number of query packets,* ***uv'*** *is the communication packet overhead for the searching stage,* ***bp*** *is backtrack packet,* ***CCID*** *is the cell code identifier.*

In order to accomplish a connected ad hoc network, 'no isolated nodes' or MNs can reach each other via multi path. Based on this, we need to find out what the minimum radio transmission range is. In our simulation, a random MN of ad hoc network is represented as a random point. Therefore, it is probable that the distance between MNs and their closest neighbours is **≤ r**. If **r = r0**, then it is likely that MN has at least one neighbour.

This is represented in (17) and (18), otherwise MN has no neighbours (disconnected) and this is represented in (19).

$$p(\xi \ \le \ r_0) = \int_{\xi=0}^{1} 1 - e^{-p\pi r^2} * Q(uv' + bp) \tag{17}$$

$$p(d(u) > 0) = p(\xi \ \le \ r_0) * Q(uv' + bp) \tag{18}$$

$$p(d(u) = 0) = p(\xi \ \le \ r_0) = 1 - \ p(\xi \ \le \ r_0) = \ e^{-p\pi r_0^2} \ * Q(uv' + n(CCID) + bp) \tag{19}$$

The goal is to create a connected network 'graph G', where there is no disconnection between MNs. **d (u) > 0, ∀u ∈ G ⇔dmin(G) > 0**. To achieve fully connected ad hoc networks, there must be a multipath from and to each MN. The probability of this scenario, with marginal independence assumed, is represented in (20). To ensure, with at least **P** probability, that no MN is isolated in the network, radio range can be set for all MNs using (21) [30].

$$p(d_{min} > 0) = \binom{n}{n} p(d > 0)^n p(d = 0)^0 = (1 - e^{-\rho\pi r_0^2})^n * Q(uv' + bp) \tag{20}$$

$$r_0 \ge \sqrt{\frac{-\ln\left(1 - p^{\frac{1}{n}}\right)}{p\pi}} \tag{21}$$

A high node degree makes an MN resilient against failures of neighbour`s MNs and links. For calculating node mobility (**M**), each node can find its location information using GPS, so that it can calculate the node mobility using (22) and (23). Equation (24) represents node mobility with transmission range **r0** with at least one neighbour.

$$x_{1=} x_0 + \left(v * (\cos\theta)\right) * M \tag{22}$$

$$y_{1=}\, y_0 + \left(v * (\sin\theta)\right) * M \qquad (23)$$

$$M(d_{min}\ > 0) = \ r_0 \geq \sqrt{\frac{-\ln\left(1 - p^{\frac{1}{n}}\right)}{p\pi}} \qquad (24)$$

7.3.2. Novel Probability of Communication Process between Active Mobile Nodes

Simulation experiments are widely used to evaluate MANET routing protocols. Similar to simulations of traditional wired networks, these experiments must model the network topology, network traffic and the routing and other network protocols.

In addition, the wireless and mobile nature of MANETs necessitate consideration of node mobility, physical layer issues (including the radio frequency channel), terrain, and antenna properties. Also, perhaps, energy and battery characteristics.

Node mobility, joined with physical layer characteristics, determine the status of link connections and, therefore, the network's dynamic topology. Link connectivity between MNs is an important factor, affecting the relative performance of MANET routing protocols.

The connectivity depends on the radio transmission range and number of MN density. Each MN contributes to the connectivity of the entire network. Communication between two active nodes can be initiated as follows:

A) Two MNs, moving in their particular self-directed modes, come within the range of each other and start communication.

B) A MN becomes active at any given time at a random place, and it happens to be in the range of communication of another MN. These initial conditions of active communication will have an impact on the calculation of the link/path metrics of the MANET.

The key factor in the mobility model that was inherent for each MN of the MANET, plays the key role in controlling the performance metrics, including link/path metrics. Two nodes are neighbours if, their intermediate distance is less or equal to their transmission range.

A new metric for measuring routing performance, called 'Probability of Communication Process', between active MNs is presented. The measurement is based on the assembled paths over randomised dynamic network topologies. The topology of the network can be represented as undirected weighted graph (25).

$$G = (V, A) \qquad (25)$$

*Where, **V** is a set of active MNs and **A** is a set of active wireless links.*

In MANET, it is important to know when the link is disconnected with surrounding nodes, as this may cause unacceptable message delivery delay. Although, an active path can be established between MNs when there are valid links connectivity, it is analytically unlikely to capture and measure the performance, due to the dynamic changes of the network topology over time.

Therefore, we use the following method ‘Sobol sequences’ to capture and measure the routing performance over many repeated network simulation scenarios. At any time **t**, the undirected weighted graph can be represented in (26).

$$G_t = (V, A_t) * M(d_{min} > 0) \tag{26}$$

*Where, $\boldsymbol{G_t}$ is subset of **G**, $\boldsymbol{A_t}$ is a set of active wireless links at any time **t**, and **V** is a set of active MNs during the simulation experiments.*

Due to the dynamic changes in the routing paths between the active MNs, the number of established paths will have to be computed and averaged over many scenarios.

Simulation scenarios were equally run for 500 times (n= 500) within 1000s. The established active paths between the nodes, throughout the simulation, were measured 500 times. The value of n can be any real number.

With variant the value of n (by increasing it), the accuracy of the result may increase. The average successful established paths can be present in (27).

$$A_t = A_0 + A_1 + \cdots + A_{n-1} \tag{27}$$

Equation (28), is derived to measure the probability of the path connectivity for one set of simulation scenario, where (29) is used to measure the probability of the path connectivity, over many set of simulation scenarios.

$$Prob_{ep} = \frac{\sum_{j=0}^{j=(T_S-1)} A_j}{Ts} * M(d_{min} > 0) \tag{28}$$

$$Prob_{ep} = \frac{\sum_{j=0}^{j=(T_S-1)} * \sum_{k=0}^{k=(n-1)} A_{jk}}{Ts} * M(d_{min} > 0) = \frac{\sum_{j=0}^{j=(T_S-1)} * \sum_{k=0}^{k=(n-1)} A_{jk}}{Ts} * \ r_0 \geq \sqrt{\frac{-\ln\left(1-p^{\frac{1}{n}}\right)}{p\pi}} \qquad (29)$$

Where, ***Probep*** *is successful probability of an established path,* ***Ts*** *is the total number of scenarios,* ***n*** *is a real number for each time the simulation ran,* ***M*** *is the node mobility.*

The simulation result presented in the following subsection will consider only the minimum node connectivity (i.e., **d=1**).

7.4. Analysis on Impact of Route, Link, and Mobility Models

In order to explain how the route, link, and MMs impacts on the performance of the MANET routing protocols, various predominance metrics are used and performance discrepancies analysed in this section.

7.4.1. Simulation Setup and Results – Mobility Models

We have chosen LANDY, and GPSR position based MANET routing protocols for performance investigation under different MMs. Both protocols were evaluated under GMM and RPGM using OPNET v14.5 simulation tools.

The MMs are computed using C-code programs, whose results are imported into OPNET simulation models Figure 45. Each node is then assigned a particular trajectory. The LANDY protocol is implemented in the OPNET as a process model in wireless MNs. The LANDY process model can be represented in a STD. MN models were constructed that included OPNET standard IEEE 802.11 physical and MAC layers, as well as custom built process models to implement the LANDY protocol.

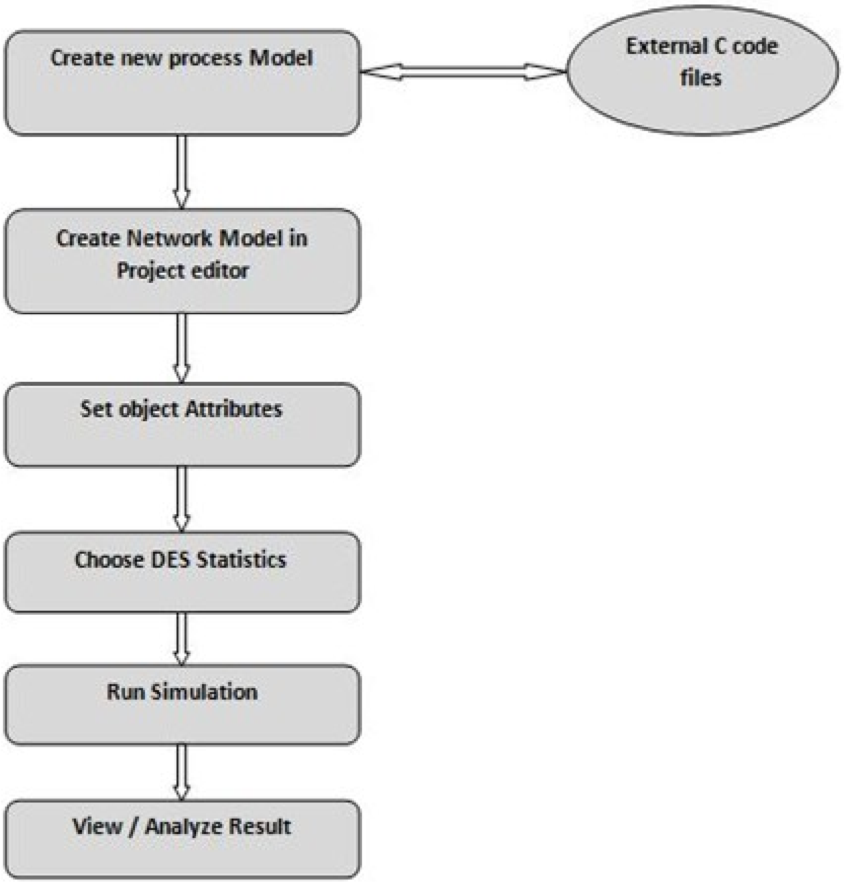


Figure 45. Process Flow for Simulations

The traffic application is a traffic generator. This traffic generator starts at 10sec during simulation. Every model has the mean speed changing from 10m/sec to 30m/sec with zero pause time. In all patterns, 500 nodes move in an area of 1500m × 1500m for a period of 1200sec, to avoid the effect of initializing and ending, and we only gather the data between 100s – 1100sec.The error bars indicate 95% confidence intervals in all the scenarios.

Six sets of source and destination pairs were selected randomly from a group of 500 MNs. Constant bit rate (CRB), used to set the rate of the transmitted data packet, which is set to 100 packets /sec, and the size of UDP is fixed to 512 bytes. The accurate adjustment of the MNs radio transmission power is a key factor in the simulation. It allows the controlling of the network topology in MANET [9, 30].

If we increase the transmission power of a MN, this will result in higher range and consequently reach more MNs, via a direct link. Otherwise, if we set the power low, this might result in isolation without any link to other MNs.

We have configured the six sets with two different power levels in Table 20. Each set will cover various volume of unidirectional links. For example, set 0.1 represents 10% MN with low transmission range and 90% with high transmission range.

This method will aid the performance investigation for scenarios with various volume of unidirectional links. The high level is assigned to MN with transmission range 300 m, and the low level is assigned to MN with 125 m transmission range.

Due to the dynamic topology of the MNs, it is not possible to determine the exact number of links, which results in routes repeatedly being assembled and broken. The MAC radio propagation bit rate is set to 11 Mb/s with frequency operating at 2.422 GHz. Table 21, represent the setting for MMs on both protocols.

Table 20. Ratio Set for Unidirectional Links

Set No.	Set 0	Set 0.1	Set 0.2	Set 0.3	Set 0.4	Set 0.5
No. of MNs	0	100	200	300	400	500

The unidirectional links results are shown in Figure 46 and Figure 47 for LANDY, GPSR as a function of radio range in the 500-node scenarios, respectively. The result indicates that at higher speed, the probability of unidirectional links occurrences is higher.

Table 21. Configuration Parameters of Mobility Models – Location Based Routing Protocols

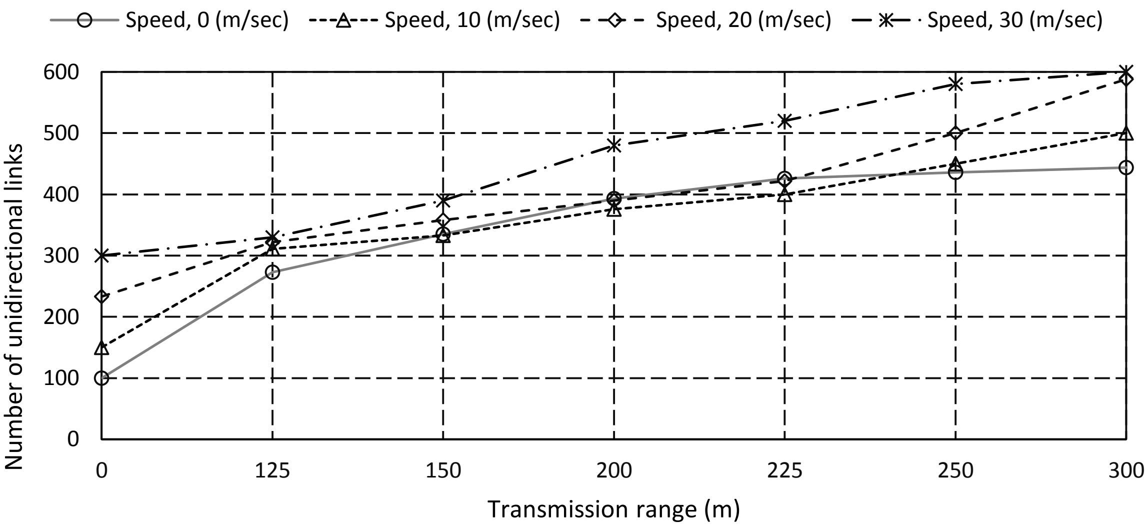
Parameter	**GMM**	**RPGM**
No. of Mobile Nodes	500	500
Speed update frequency	2.5 s	NA
Angle std deviation	450	NA
Speed std deviation	1.5 m/s	NA
Group deviation	NA	2
Pause time	NA	0 s
No. of groups	NA	50 groups

Routes between the MN become unstable at higher speed, due to the dynamic topology and possibly breaks, leading to unidirectional links. The results show that GMM generate more unidirectional links compared to RPGM, on both protocols. At speed of 0 m/s crossing set 0 in Figure 45 and 46, on both protocols, we have noticed a small number of unidirectional links generated.

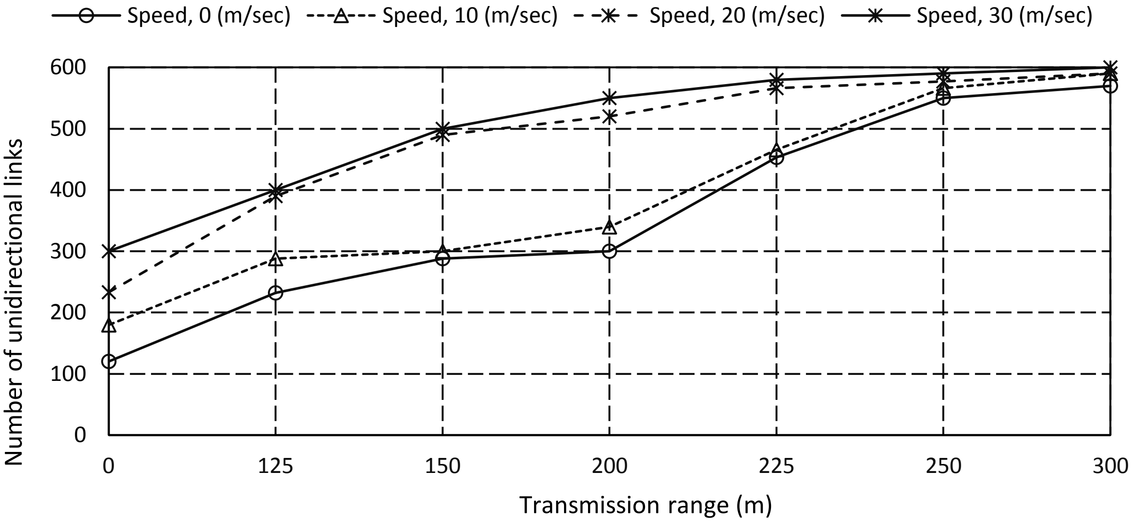
Due to the interference by neighbouring MNs, packet dropping results. Also, with increasing the speed of the MNs, this will lead to link breaks frequently, and resulting in interpretation as 'unidirectional links' by both routing protocols.

When the number of unidirectional links fluctuate at a high rate mobility rate, the slight drop is due to the fact that the number of RREQ 'Route Request' packets sent by the source node decreases, and it indicates that either the routing paths have been successfully constructed, or there exists more bidirectional links in the network than the unidirectional links.

Also, low transmission range does not always provide an increase in number of unidirectional links, due to the impact of other factors, such as the behaviour of mobility model and speed MNs.

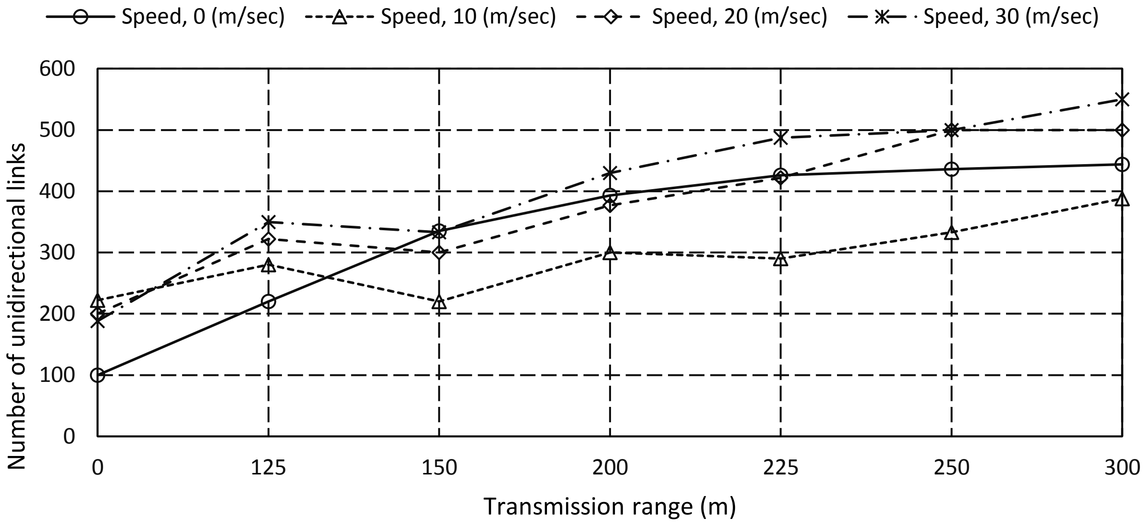


(a) GMM

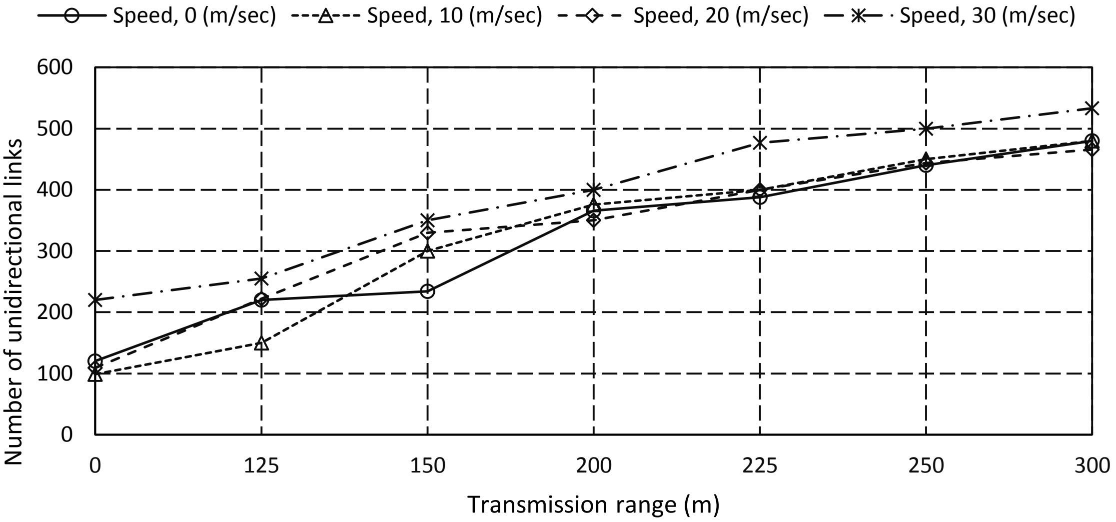


(b) RPGM

Figure 46. Unidirectional Links vs. Radio range – LANDY



(a) GMM



(b) RPGM

Figure 47. Unidirectional Links vs. Radio range – GPSR

The results of the average RREQ packet sent by each source MNs are shown in Figure 48 and Figure 49 for LANDY, GPSR as a function of radio range in the 500-node scenarios, respectively. The source MNs send RREQ at route discovery and recovery process of route failure, on both routing protocols. Results indicate that, the higher mobility of MNs result in increasing the production of RREQ in the network.

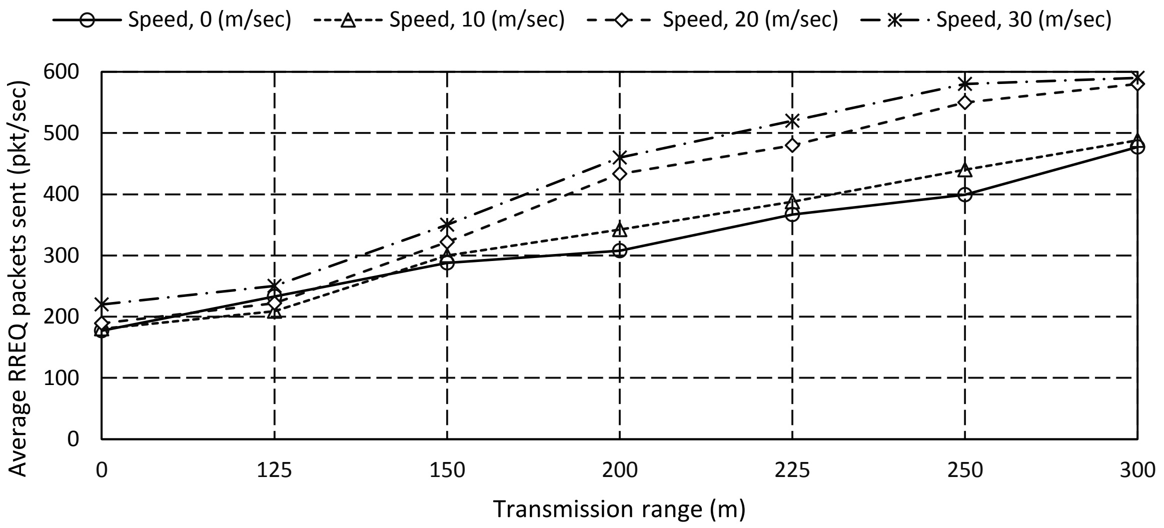
This causes routing overhead. With speed increasing more overhead is generating in both protocols, but LANDY have less overhead than GPSR. Also, observation of simulation experiments, shows that more than 80% of routing packets in the network are created by the RREQ packet of MNs.

In general, the performance of GPSR drops with increasing number of nodes set with low transmission range, but LANDY perform better compared to GPSR. Results also show that, the impact of RPGM on routing performance is minimal, compared with GMM.

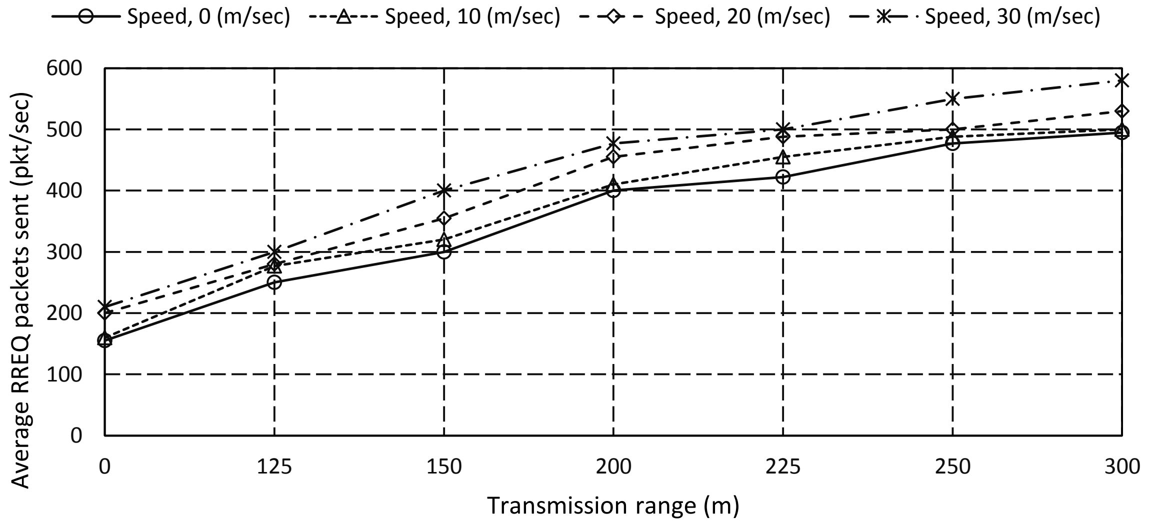
Such performance is due to MNs closeness, which restricts movement to within a small area around the reference point. As a result, link connectivity increases, leading to less unidirectional links occurrences. On the other hand, MNs in GMM are uniformly distributed, consequently nodes are more vulnerable to form unidirectional links.

In addition, results show with the speed increasing, each metric is getting worse in some way. These results exist, because the topology of the network is more unstable with the speed increasing.

As a result of the RPGM model, which only has pause time in simulation boundary, and the MNs need to keep moving in the same direction until they reach the border of the simulation area. The metric in RPGM model is better than that of GMM model.

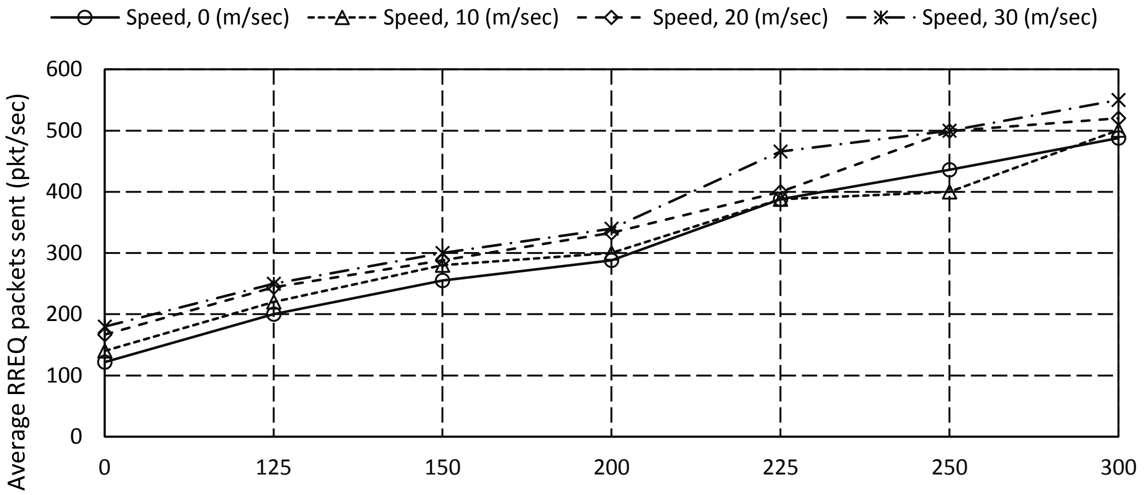


(a) GMM

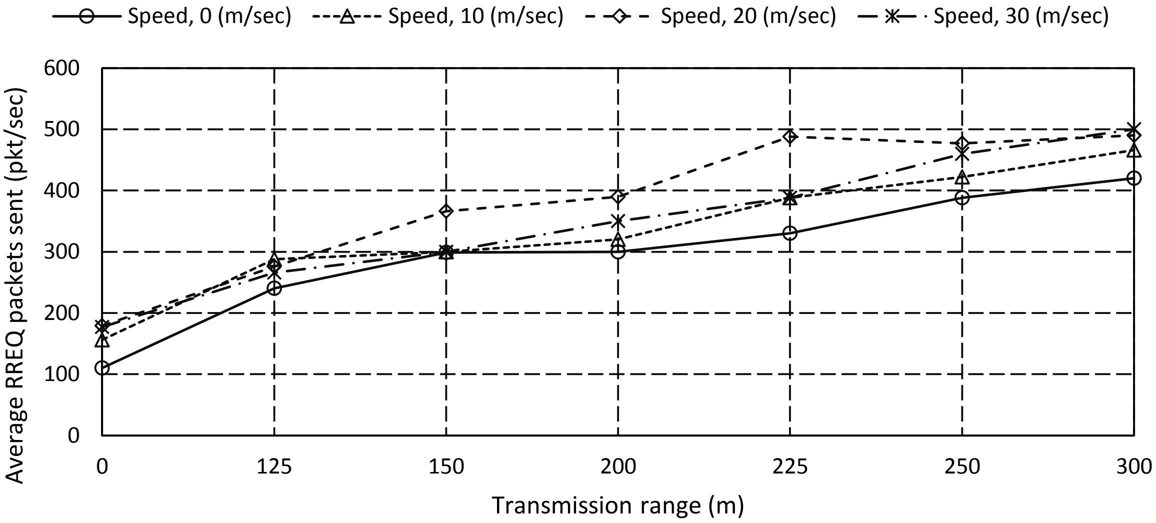


(b) RPGM

Figure 48. Average RREQ Packet Sent vs. Radio Range – LANDY



(a) GMM



(b) RPGM

Figure 49. Average RREQ Packet Sent vs. Radio Range – GPSR

7.4.2. Simulation Setup and Results – Link and Route

In order to investigate the probability of link connectivity, and the probability of communication process/ path between active MNs, we have configured the setting in Table 22 for our simulation scenarios. Each simulation is repeated using 500 different scenarios generated from random seeds.

The results of the link connectivity probability is shown in Figure 50 and Figure 51 for LANDY, GPSR as a function of transmission range in the 500-node scenarios, respectively.

The link connectivity probability varies for each routing protocol under a different mobility model.

The highest percentage of link connectivity probability is presented by GMM (93%) for set 0.5, compared with RPGM (81%). LANDY overcame GPSR in both cases. We compare our result to [30] section 4.3. In [30], simulation study considered only nodes in the ‘inner zone”.

The disadvantage of this method, with increasing r0, is the number of nodes decrease (MNs which contribute to the statics of the simulation). In our simulation study, we considered both scenarios, the centre and the borders.

Table 22. Configuration Parameters - Link and Route – Location Based Routing Protocols

Parameters	**Value**
Simulation Area	1500 x 1500 sq.meters
Mobility Models Used	GMM, RPGM
Antenna type	Omni antenna
Traffic model	CBR, UDP
Transmitter range	300 m
Routing Protocol	DSR , AODV, DSDV, OLSR
MAC Protocols	IEEE 802.11 DCF
Data traffic size	512 bytes
Data packet rate	100 packets/sec
Simulation time	1200 sec
Number of Nodes	500
Mobility Speed	10, 20, 30 m/sec
Simulation software	OPNET

We then went one step further and asked the question: What is the minimum radio range for the above scenarios in connected MANET? The condition $M\ (d_{min} > 0)$ is important, and essential for a graph to be connected. Equation (18) can be used to calculate transmission range r0 for lower bound, in order to achieve connected network.

When increasing the number of MNs with low transmission range, all the MMs showed a dramatic decrease in the link connectivity probability, especially in set 0.1 and 0.3.

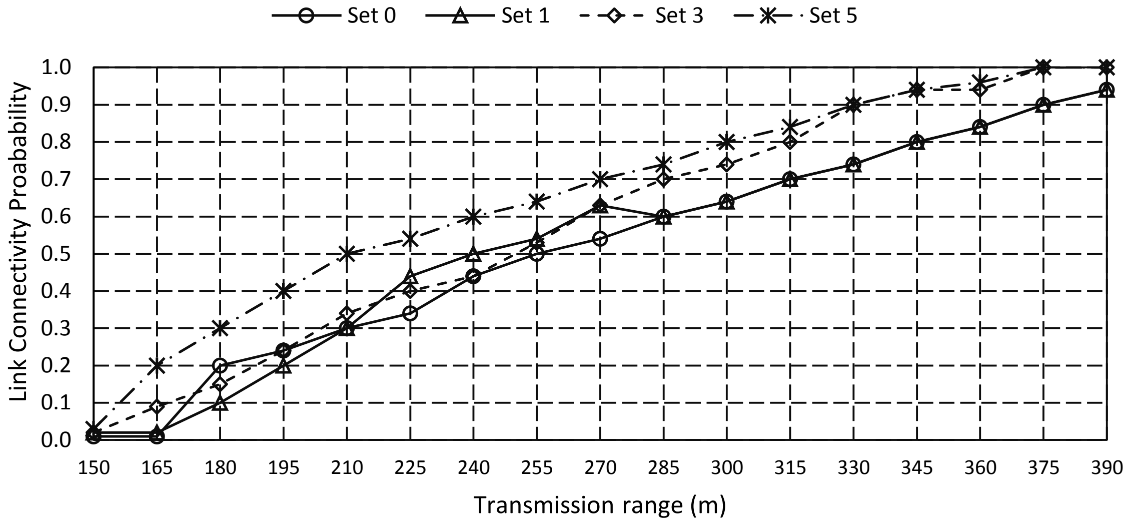
This behaviour is as a result of the presence of unidirectional links, which impact and reduce the communication process between the MNs and its neighbours. It is apparent, between set 0 and set 0.3 on both MMs, thus the link connectivity probability fluctuate as much as %62. In addition, the outcome of intense observation of the results, suggests that occurrence of all bidirectional links between the neighbouring MNs may not guarantee least a fully connected mobile network.

With continuing the increase in the MNs with low power transmission Ptrans(set 0.5), the link connectivity probability as continue to fluctuate. In order to reach a value alike link connectivity probability of set 0, the Ptrans has to be marginally increased. This can be seen in Figure 49 and Figure 50. By increasing the Ptrans in set 0.5, we can achieve similar performance to set 0.

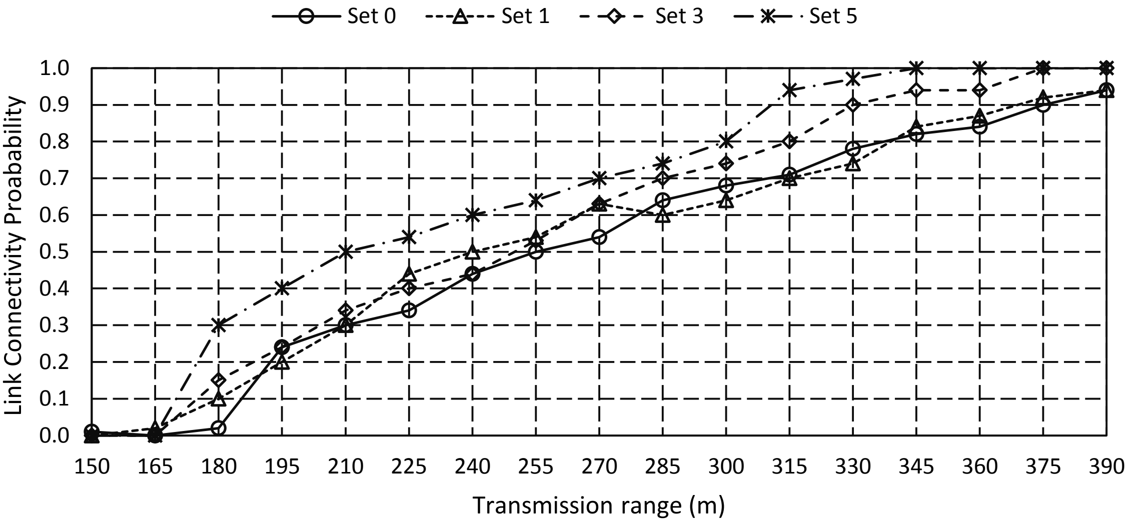
Also, results show that the probability of ‘k-connected’ network, changes dramatically with the increase of r0. In addition, result shows equation [17] is valid in a simulation area restricted with border effects, which is necessary for finding accurate range or density that create connect network.

Also, results indicate that RPGM perform better than GMM with regards offering lower connectivity on both protocols. Furthermore, results show that impact of the unidirectional links on the performance of the routing protocols when Ptrans is nominal (i.e., 250), which is commonly implemented in commercial outdoor radio interface.

Increasing Ptrans beyond the nominal value leads to increase in the channel load, and this effect is not desirable. Also, it will lead to increase in the routing overhead.

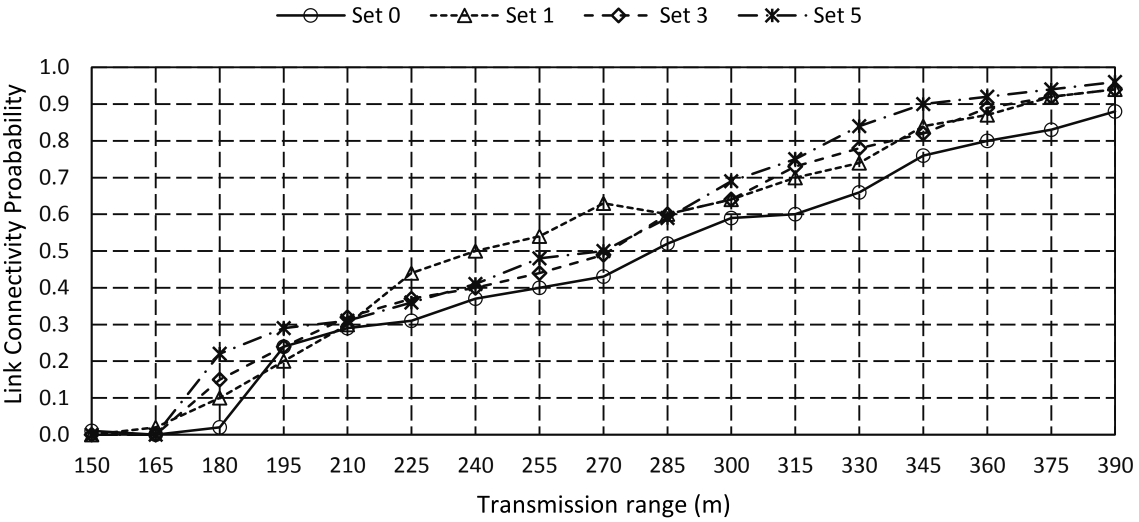


(a) GMM

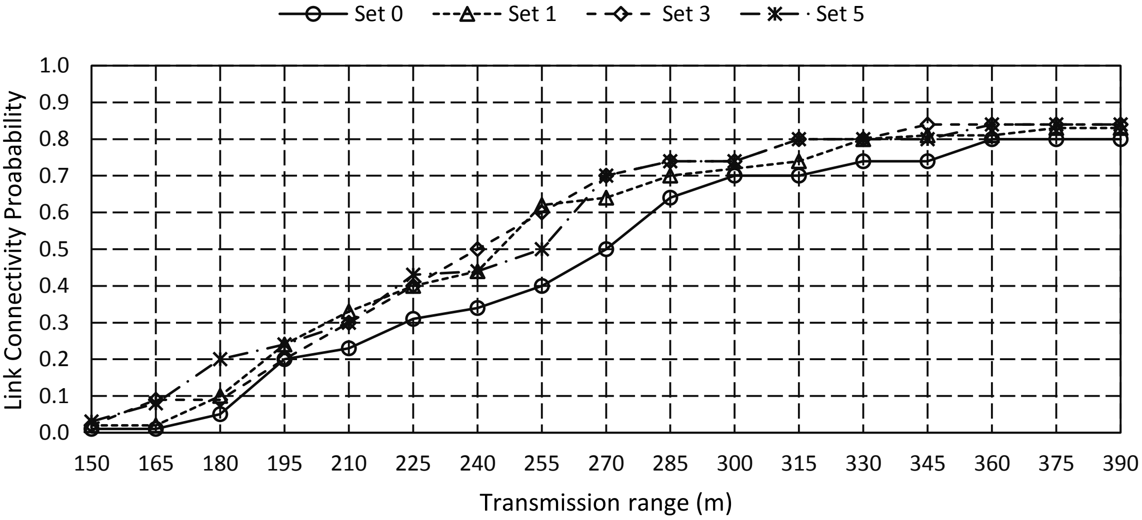


(b) RPGM

Figure 50. Link Connectivity Probability vs. Transmission Range – LANDY



(a) GMM



(b) RPGM

Figure 51. Link Connectivity Probability vs. Transmission Range – GPSR

The results of the Path connectivity probability are shown in Figure 52 and Figure 53, for LANDY, and GPSR as a function of transmission range in the 500-node scenarios, respectively. We measure the path connectivity probability, by measuring the number of successfully established routes to the number of successful RREP 'Route Reply' received at the source MNs.

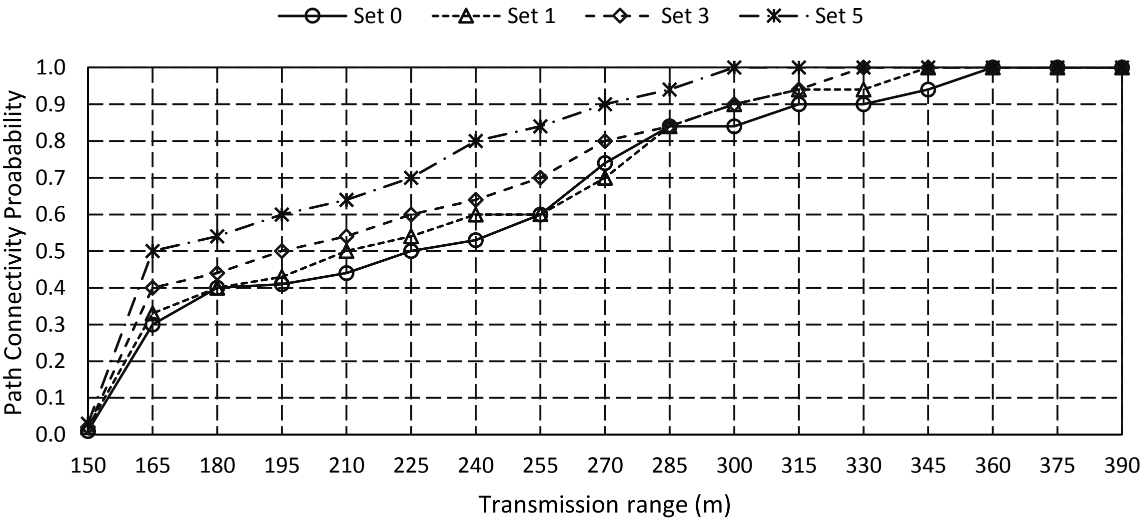
The process of receiving RREP from the destination by the sources MNs indicates that the target MNs received the RREQ packet (i.e., creating forward route) and reply by sending a RREP packet (i.e., creating reverse packet). The process of successful bidirectional communication leads to successful established route between the MNs.

Figure 51, and 52 shows the path connectivity probability for both protocols under GMM and RPGM. These scenarios were repeated 500 times, with different settings, for MNs Ptrans various between 150 to 400m. The results show accurate details about the unidirectional link impact on the performance of the routing protocols compared to the link connectivity probability in Figure 50, and 51.

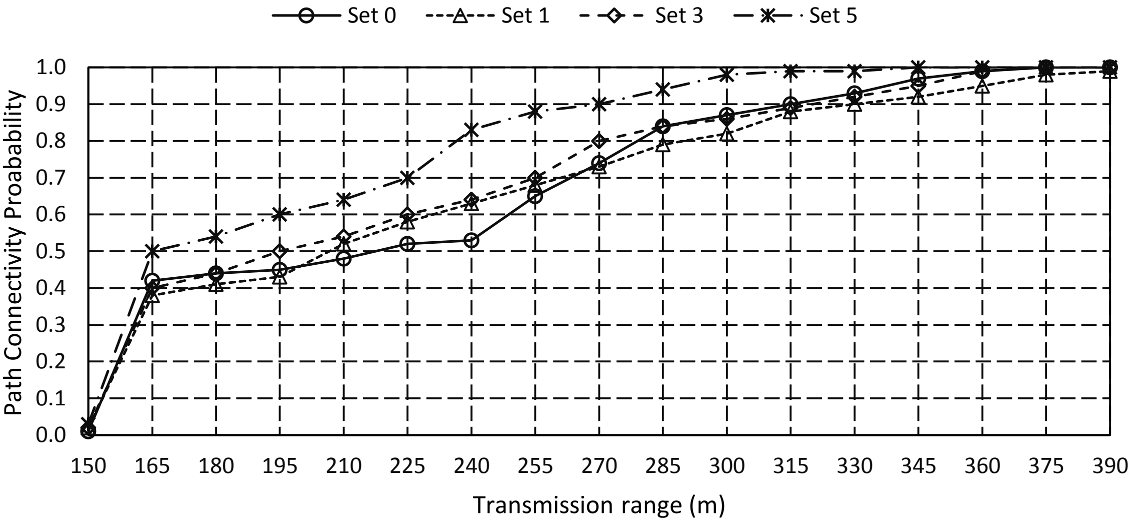
Results indicate that the path connectivity probability for set 0 MNs shows better performance compared to set 0.1, and set 0.3. When Ptrans set to 250 m, results show that routes between MNs in the network, established successfully during the simulation run between 400 and 500. This indicates guaranteed route establishment at this setting. The path connectivity probability in GMM is greater than RPGM at Ptrans > 250 m. Generally LANDY perform better than GPSR, in relation to established path ‘path connectivity probability".

The performance of GPSR fluctuate significantly for set 0.3 and 0.5 across both MMs. The Path connectivity probability fluctuate as much as 65% between set 0 and 0.5, as result of the high number of unidirectional links between the MNs in the network.

GPSR has no unidirectional link detection mechanism, as result of that path between the MNs will be unstable will breaks frequently. Remarkable observation is in accordance with the termed ‘phase transition' [30] section 5.2. We can get a similar result to [30] by increasing node density **ρ** for a given transmission range **r0**. This solution is valid in area without border effect, in order to achieve higher connectivity in MANET.

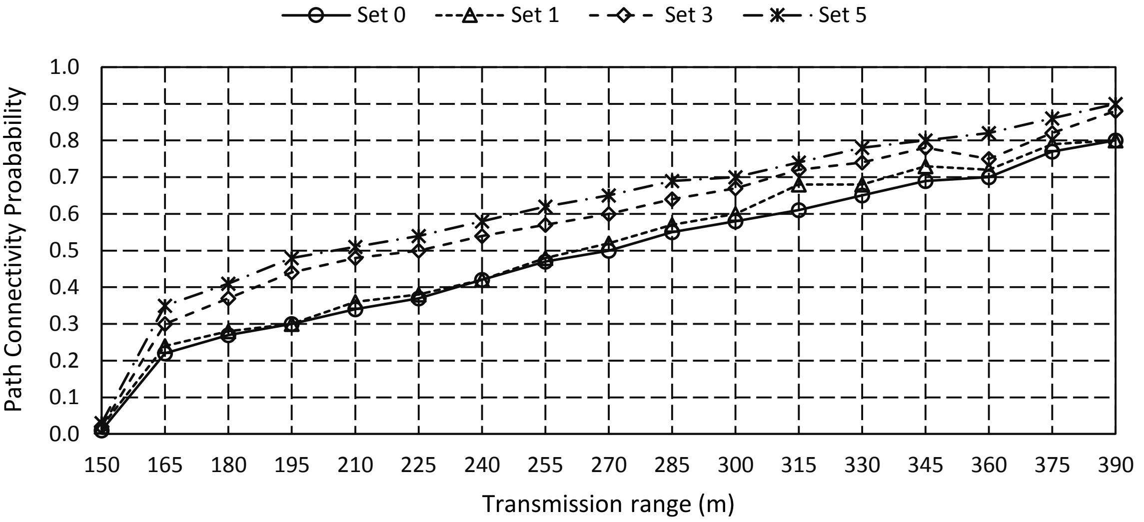


(a) GMM

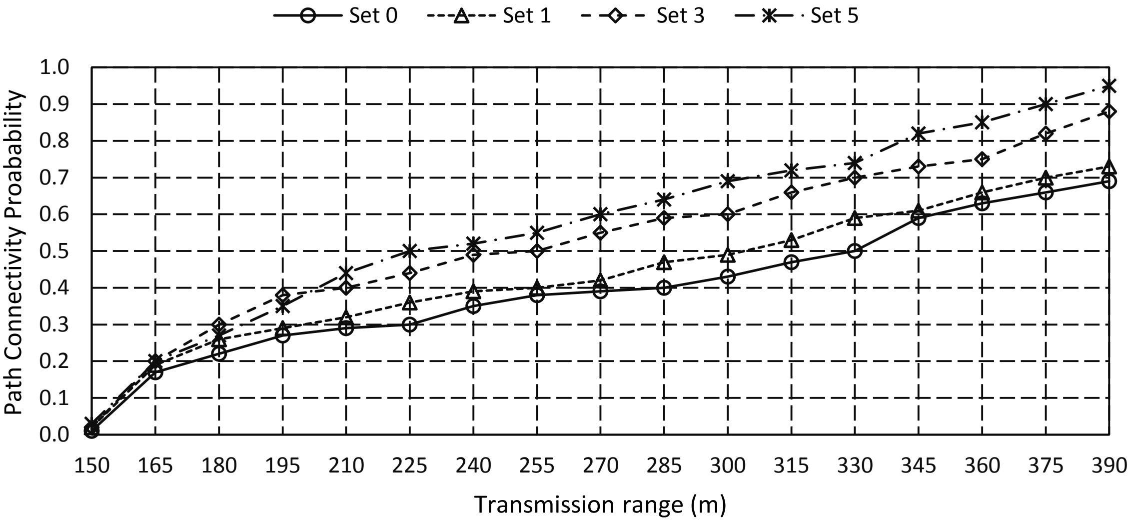


(b) RPGM

Figure 52. Path Connectivity Probability vs. Transmission Range – LANDY



(a) GMM



(b) RPGM

Figure 53. Path Connectivity Probability vs. Transmission Range – GPSR

7.5. Chapter Summary

We have analysed the performance comparison of the routing protocols LANDY, and GPSR using OPNET simulator. In the performance testing, the effects of the route, link and MMs on the performance metric of MANET routing protocols, have been analysed. The simulation results indicate that, even by setting the same parameters, different MMs have a diverse impact on the performance evaluation of protocols.

Therefore, choosing an appropriate MM, as well as setting applicable parameters, serve as the key role for protocol evaluation. It is found that protocols that have link layer support for link breakage detection, are much more stable. The performance of the protocols differs slightly during different network loads.

The most apparent difference is the byte overhead. While LANDY has a rather unaffected overhead, it increases for GPSR during high loads. A higher sending rate causes the protocol to detect broken links faster, thus reacting faster; this leads to a slight increase in control packets, which affects the byte overhead. The increased send rate also sets demands on the send buffer of the routing protocol. Whenever congestion occurs, packets are dropped.

The faster a routing protocol can find an alternative route, the less time the packets have to spend in buffers, meaning a less probability of packet drops.

From a network layer perspective, changes in link connectivity trigger routing events such as routing failures and routing updates. These events affect the performance of a routing protocol. For example: Increasing packet delivery time, or decreasing the fraction of delivered packets, leads to routing overhead, e.g., for route update messages.

Therefore, given physical layer assumptions about link connectivity, are critical to the significance of simulation results for MANET routing protocols. In addition, more coordinated movements of the nodes reduces the number of control packets required to be distributed over the network, and reduces the routing overhead.

CHAPTER 8. REALISTIC SCENARIOS

It is important to test and check the behaviour of the position based routing protocols in a more realistic scenario. Hence, we have carried out some simulations on different scenarios assumed to be realistic. Below are the three scenarios that we have carried out simulations on;

1- Scenario 1, with low movement factor.
2- Scenario 2, with fairly large movement factor.
3- Scenario 3, with some relatively slow nodes and some very fast nodes.

The scenarios mainly test the protocols:

- Ability to respond to local changes for long links.
- Ability to cope with large volume of traffic.
- Message overhead with low mobility factor.
- Ability to respond to fast link changes and fluctuating traffic.
- Message overhead with constant topology updates.
- Ability to work with both slow and fast changing network topologies.
- Ability to cope with network partitioning.

Different mobility patterns have been selected to represent real movement scenarios related to FCS. The MANET network simulations are implemented using OPNET Modeller simulation tool. The MMs are computed using C-code programs.

Each node is then assigned a particular trajectory. The LANDY protocol is implemented in the OPNET as a process model in wireless MNs. The LANDY process model can be represented in a STD.

MN models were constructed that included OPNET standard IEEE 802.11 physical and MAC layers, as well as custom build process models to implement the LANDY protocol. The scenarios simulate the MANET nodes moving in a 2-D mobility region, and in this implementation the height dimension is omitted. The MMs are used to govern the movement of the nodes. Each scenario performs 500 simulation runs with different random seeds, and the mean of the metrics are compared.

The common parameter setting of the simulation is shown in Table 23. The traffic destination is a random node. The traffic application is a traffic generator. This traffic generator starts at 10s during simulation.

Table 23. Parameters Configuration Realistic Simulations

Parameters	Value
Simulation Area	1500 x 1500 sq.meters
Mobility Models Used	GMM, RPGM
Antenna type	Omni antenna
Traffic model	CBR, UDP
Transmitter range	300 m
Routing Protocol	DSR , AODV, DSDV, OLSR
MAC Protocols	IEEE 802.11 DCF
Data traffic size	512 bytes
Data packet rate	150 packets/sec
Simulation time	1200 sec
Number of Nodes	500
Mobility Speed	0, 10, 20, 30, 40, 50, 60 m/sec
Simulation software	OPNET

The packet inter-arrival time is exponentially distributed with mean value of 10s. For analysing how variation speed impacts on the performance, two models have been set with various pause time (10 - 60 sec), and every model has the mean speed changing from 10m/sec to 60m/sec. In all patterns, 500 nodes move in an area of 1500m × 1500m for a period of 1200secec, to avoid the effect of initializing and ending, the data was gathered between 200sec – 1000sec. Scenario files were generated with varying node speeds.

The following performance metrics were obtained from the two MMs (GMM, and RPGM): Throughput, PDR, routing overhead and average end-to-end delay. These metrics are suggested by the MANET working group for routing protocol evaluation [14, 22, 24, 27].

8.1. Performance Metric

The performance evaluation, as well as the design and development of routing protocols for MANETs, requires additional parameters. According to the IETF RFC 2701, we have selected the following metrics to be collected during the simulation, in order to evaluate the performance of the different protocols.

When evaluating the performance of routing protocols in MANET, it is important to check against certain parameters for their performance.

8.1.1. Throughput

Throughput is defined as the ratio of total data that reaches destination node from the source node. The time it takes the destination node to receive the last message, is called throughput [13]. Throughput is expressed as bytes or bits per sec (byte/sec or bit/sec).

8.1.2. Control Overhead

The Control Overhead consists of HELLO messages and LC messages. Due to the broadcast nature of the control message delivery, the packets are measured by summing up the size of all the control packets received by each MN during the whole simulation period.

Many small control information packets would mean that the radio medium, on which packets are sent, is acquired more frequently. This would impact massively on the performance, power and network utilization.

8.1.3. Packets Delivery Ratio

The delivery ratio is the ratio of the number of successfully delivered data packets to the number of total data packets. It is the metric of the data transmission reliability. The MAC layer protocol is IEEE 802.11 DCF CSMA/CA. The free space path loss model is used in the simulations to determine the transmitter power.

8.1.4. Average End-to end Delay

The average end to end delay, can be defined as the time taken for a data packet to be transmitted across a network from source node to destination node.

8.2. Simulation Scenarios Description, Setup and Results

Below are the description and results of the scenarios.

8.2.1. Scenario 1, with Low Movement Factor.

In scenario 1, we simulate a conference with 500 low mobility attendees, and they can communicate between each other. In this scenario the area is divided into three sections:

Section1 - Presenter sector: The presenter is travelling within his region, and can communicate to the nearest neighbour from the audience.

Section 2 - Spectators sector: The spectators are semi-static. But spectators might move outside their section and return to it, which result in link breakage for stable route and dynamic network.

Section 3 - External spectators section: This includes any attendee that is outside the conference hall, and trying to communicate to an internal spectators that are attending the conference session. In this scenario, there are obstacles between the internal and external users. i.e. wall or partitions.

The characteristics of this scenario:

- Low movement, only 20% of the attendees are travelling during anytime.
- Stable connection and long lasting with several hops.
- Limited number of obstacles within the conference region.
- Traffic is focused between the attendees and the presenter.
- Interference exists due to the transmission between the attendees, which results in local congestion.
- Maximum speed is 20 m/s.

The Results of the routing overhead are shown in Figure 54 and Table 24, in the 500-node scenarios, respectively. The error bars indicate 95% confidence intervals. Results indicate that performance of the routing protocol varies over different MMs. In addition, more coordinated movements of the nodes, reduces the number of control packets required to be distributed over the network, and reduces the routing overhead.

Routing overhead can be determined by quantifying the effect per packet and number of path searches. LANDY and GPSR broadcast routing protocol packets proactively, in a nearly constant interval.

Results show, that LANDY has a smaller overhead than GPSR and GRP as the number of link searches are small. GRP have a large number of routing control messages due to the topology changes. It is important to note that the location service will increase the routing control overhead.

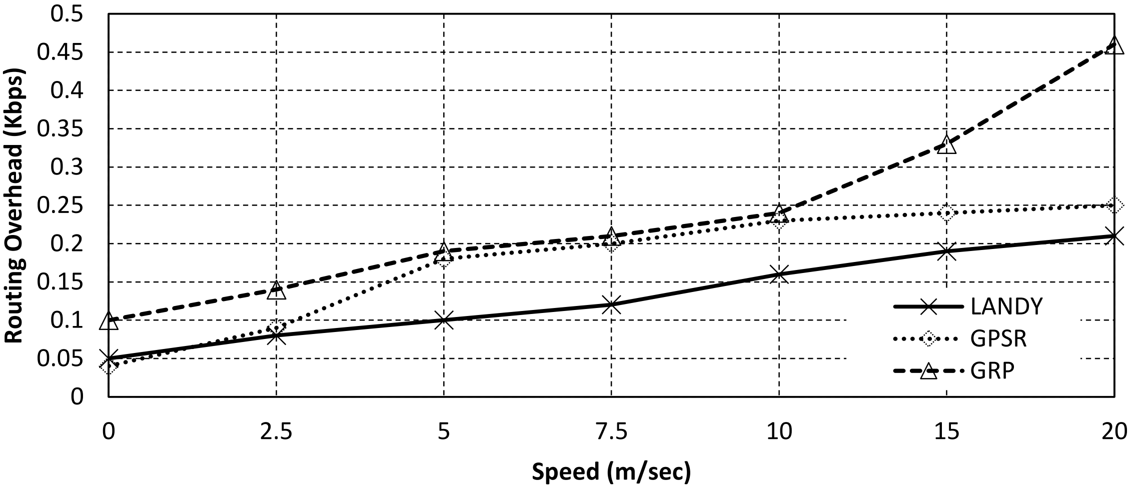
In contrast, LANDY has less overhead than GRP and GPSR among both MMs. The routing overhead, increases with the speed of the MNs. RPGM model gives minimum overhead as it supports the group movement and hence ensures more reachability. In addition, with increased speed, each metric is deteriorating in some means. The GMM model has the highest routing overhead, and shortest average hop count.

The RPGM model is the reverse. These results exist since the nodes in GMM model are often travelling near the centre of the simulation area, but the nodes in RPGM model can only change direction until it reaches the border of the simulation area.

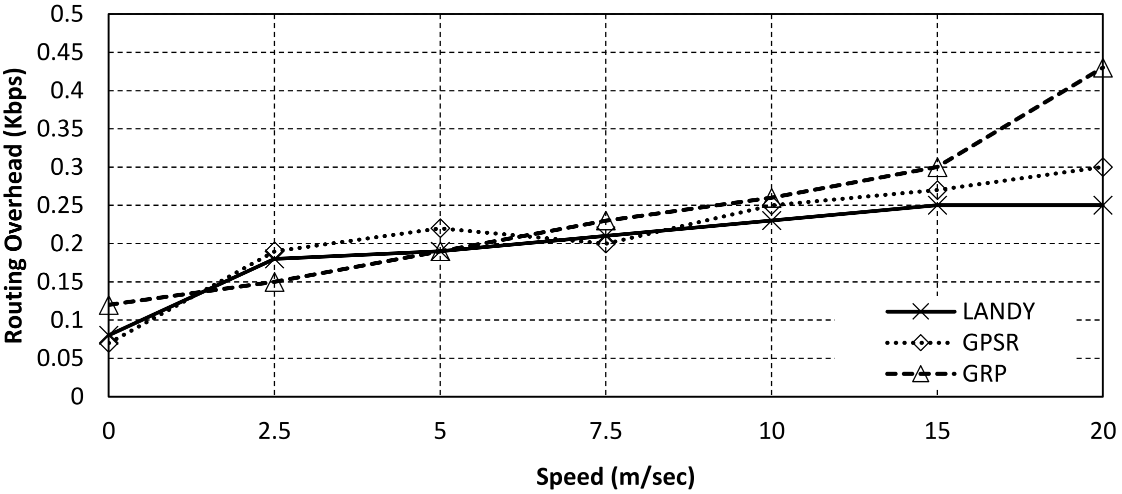
Therefore, the topology of the network can more easily be partitioned in GMM model than in that of RPGM. Moreover, the RPGM model through the probability of moving; a MN can go a longer distance before changing direction. It alleviates the sharp turnings and sudden stops; by changing the setting of MN. The probability of the MN continuing to follow the same direction is higher than the probability of the node changing directions.

The percentage of packets received using LANDY is high even when mobility increases. This result indicates that these kinds of protocols will be desirable for high mobility networks. GPSR is dependent on periodic broadcast which shows a rather poor result. In addition, a large byte overhead would mean a larger wasted bandwidth.

Many small control information packets would mean that the radio medium, on which packets are sent, is acquired more frequently. This would impact massively on the performance, power and network utilization. The routing overhead increases with the speed of the MNs. RPGM model gives minimum overhead, as it supports the group movement and hence ensures more reachability.



(a) RPGM



(b) GMM

Figure 54. Routing Overhead vs. Speed – Scenario 1

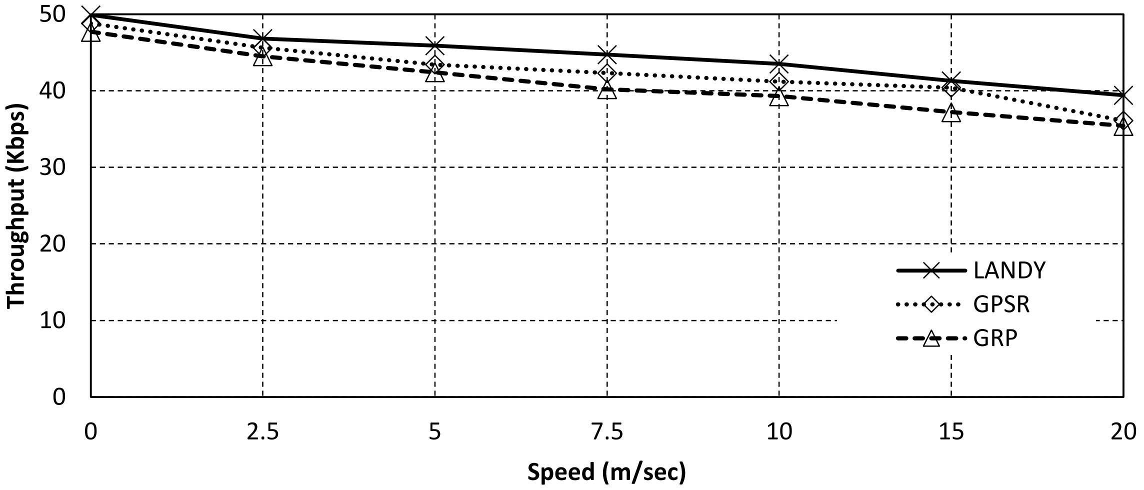
The results for throughput are shown in Figure 55 and Table 24. The rate of packet throughput increases gradually, according to the increasing number of nodes in all protocols (GRP, GPSR and LANDY). The error bars indicate 95% confidence intervals.

As shown in Figure 55, there are a few differences between LANDY and GPSR in section of speed between 0 – 20 m/s. LANDY successfully increased the rate of packet throughput as high as 99%. The reason why it is a large performance improvement, is that the numbers of alternative routes are not limited in the network which comprises of a many nodes. In overall, LANDY delivers the highest throughput and GRP is the lowest.

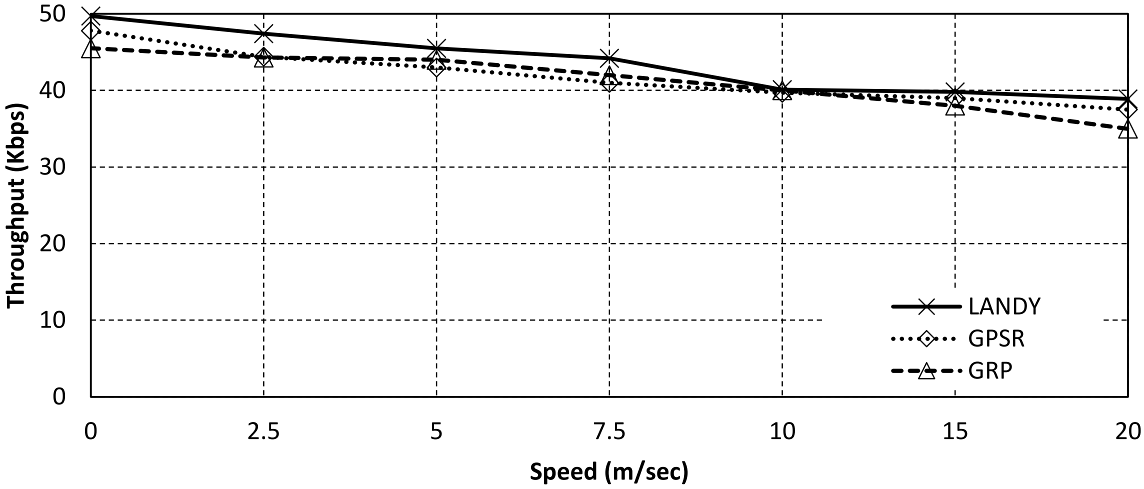
When maximum speed is varied, LANDY still delivers the highest throughput and GRP gives the lowest throughput.

By observing the packet throughput, the more a node moves, the more nodes that consist of a link are changed, and link error can be generated frequently. Therefore, LANDY packet processing ratio improves upon GRP and GPSR, in setting the shortest path. GRP packet ratio is lower, due to link errors increasing as a result of faster node movement.

But in LANDY, packet throughput is decreased little, when the maximum velocity of nodes is 20 m/sec. The efficiency is 50%. This is logical, because small packet drops will, of course, produce higher throughput.



(a) RPGM



(b) GMM

Figure 55. Throughput vs. Speed – Scenario 1

In end-to-end delay scenario, it should exhibit a lower performance when the number of nodes are under 500, because alternative longer routes might be selected instead of the shortest path. The end-to-end delay is lower in the case where more than two alternative routes can be selected, or many alternative routes.

Figure 56, and Table 24 show the average end-to-end delay of LANDY, GRP and GPSR. The error bars indicate 95% confidence intervals.

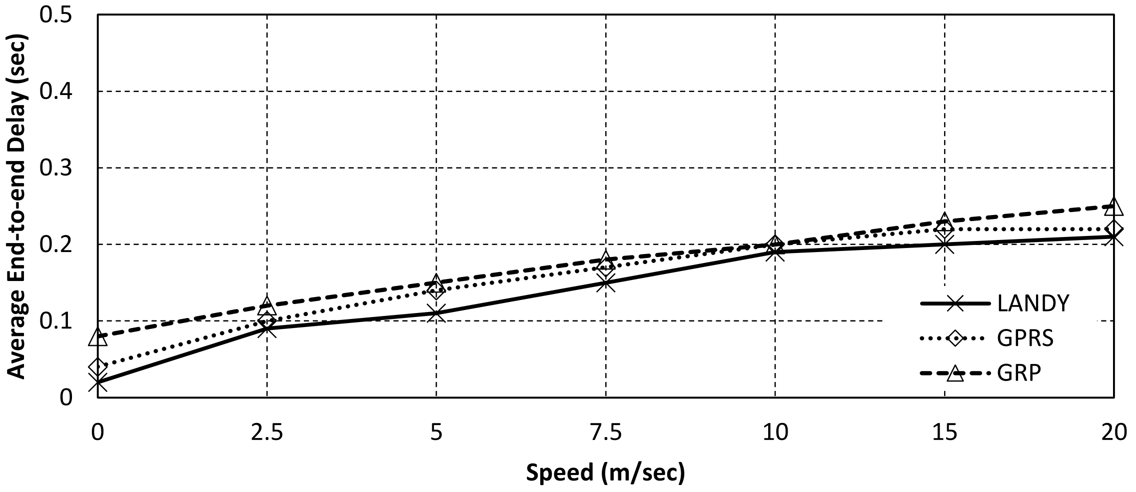
Since LANDY searches the mobile node’s future position instead of current position, it searches the path from the source to the destination faster than GPSR.

Thus, the average end-to-end delay of LANDY is lower than GPSR. When the number of nodes are between 100 and 300, GPSR has the highest average end-to-end delay, and it decreases for GRP and LANDY. With increasing the number of nodes, the value of average end-to-end delay for GPSR will be highest among the three protocols and it is the lowest for LANDY. When the speed is 0, GRP has the highest average end-to-end delay.

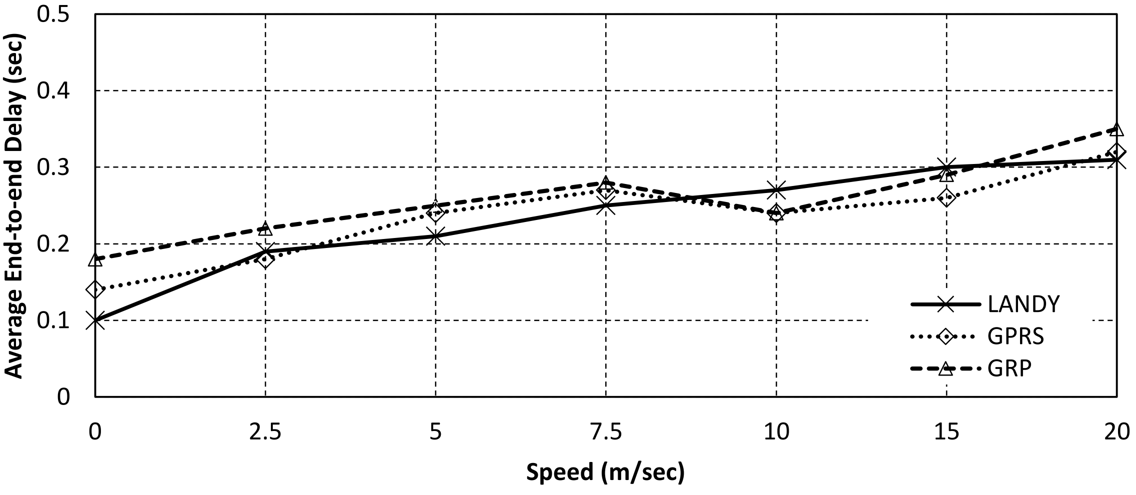
When the speed is increased to 20, the value of the end-to-end delay increases for GRP, LANDY and GPSR. In overall, GPSR has the highest average end-to-end delay, and LANDY has the lowest reading.

The end-to-end delay time is massively affected when network speed is at a slow rate. As a result of little or no mobility of nodes, error occurs in the entire path and so there is a greater chance that it searches paths consisting of the same nodes.

In this case, it cannot be effective even if it selects a path taking mobility in to consideration. Moreover, LANDY is most likely to have a larger number of nodes between source and destination node than GPSR. Therefore, more nodes can participate in communication.



(a) RPGM



(b) GMM

Figure 56. Average End to end Delay vs. Speed – Scenario 1

The packet delivery ratio results are shown in Figure 57 and Table 24 for LANDY, GPSR and GRP as a function of speed in the 500-node scenarios, respectively. The error bars indicate 95% confidence intervals. The delivery ratio of LANDY is higher than GPSR and GRP. The delivery ratio of LANDY remains high at all speeds.

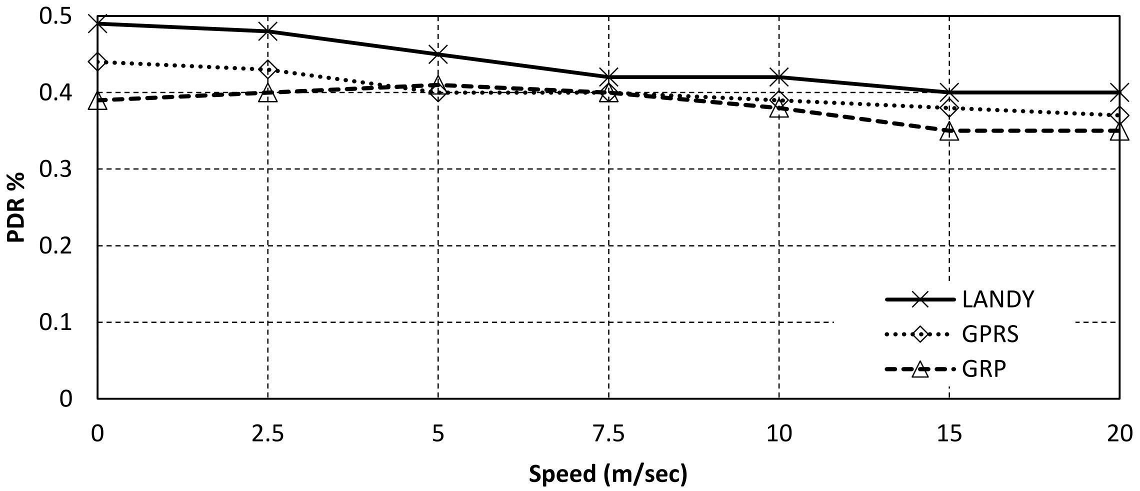
Figure 57 (a) shows that the packet delivery ratios in RPGM for the three protocols, do not have sudden changes when the speed of the mobile node increases.

All the three protocols perform well under RPGM. LANDY has the highest packet delivery ratio when compared to GPSR and GPR. In GPR there is significant decrease in the packet delivery ratio when the speed of the MN increases. It is obvious that when the MN moves with greater speed there are more chances for link breakage, resulting in less packet delivery ratio.

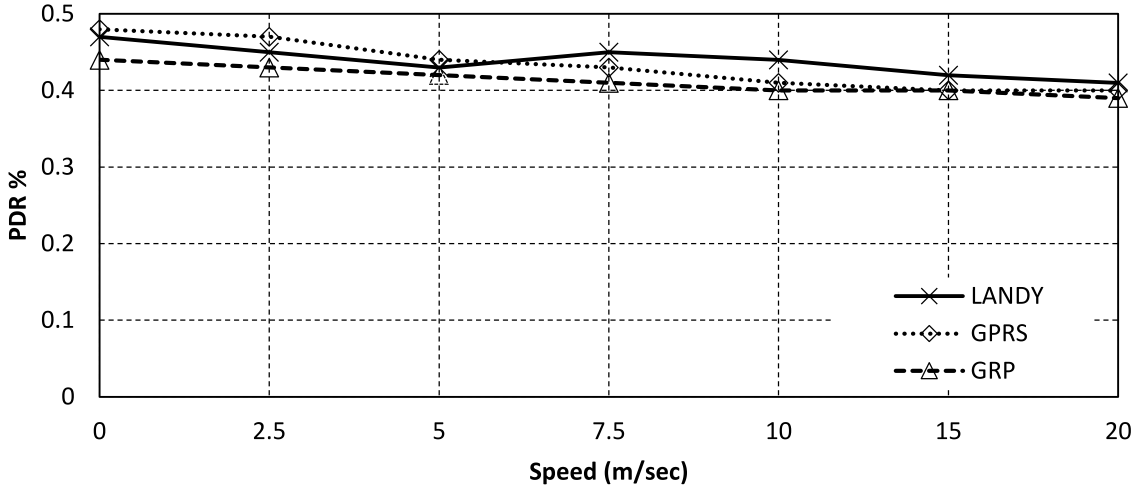
The throughput of GRP protocol depends entirely on the mobility model, and not on the speed of the MNs. GMM mobility model gives the better packet delivery ratio for GRP and RPGM gives the worst packet delivery ratio because of the lower reachability.

This ordering, from the best to worst, is roughly predicted by link changes. LANDY is able to maintain high throughput for nearly all MMs even as the speed increases. This is due to LANDY using locomotion, instead of current position, to find the mobile node's locomotion trajectory to predict the future position of MNs.

It reduces the impact of the inaccuracy of neighbours' positions on the routing performance, provides a shorter routing and avoids routing loop or routing failure.



(a) RPGM



(b) GMM

Figure 57. PDR vs. Speed – Scenario 1

Table 24. Simulation Result - Scenario 1

(a) RPGM

Parameters	**Routing protocols**		
	LANDY	**GRP**	**GPSR**
Received	% 99	% 98.83	% 98.93
Send	50510	50510	50510
Dropped	255	298	272
Throughput	44.5	42.5	40.9
Average End to end delay	0.21	0.25	0.22
Routing Overhead	0.21	0.46	0.25
PDR	0.4	0.35	0.38
Average hop count	4.52	6.34	4.97
Received packets	50255	50212	50238

(b) GMM

Parameters	**Routing protocols**		
	LANDY	**GRP**	**GPSR**
Received	% 99.01	% 98.85	% 98.94
Send	50510	50510	50510
Dropped	250	292	270
Throughput	43.6	41.7	41.2
Average End to end delay	0.31	0.36	0.32
Routing Overhead	0.25	0.44	0.3
PDR	0.42	0.39	0.4
Average hop count	4.32	6.04	4.65
Received packets	50260	50218	50240

8.2.2. Scenario 2, with Fairly Large Movement Factor

In scenario 2, we simulate an event or activity with 500 large mobility attendees, and they can communicate between each other and change positions regularly.

The characteristics of this scenarios:

- High movement, 75% of the attendees are travelling during anytime. They change their position frequently, which result in dynamic network.
- Unstable connection and short lasting with fewer hops.
- Large number of obstacles within the event or activity region.
- Interference exists, but lower than scenario 1 due to the transmission between the attendees.
- Traffic is not focused, and it is spread across all the event region.
- Communication is limited between the attendees, due to the dynamic network layout and constant position changes.
- Maximum speed is 60 m/s.

The results of the routing overhead are shown in Figure 58 and Table 25, in the 500-node scenarios, respectively. The error bars indicate 95% confidence intervals.

Results show, that LANDY has a smaller overhead than GPSR and GRP, as the number of link searches are small. The routing overheads of LANDY are nearly constant. GPSR have a large number of routing control messages due to the topology changes.

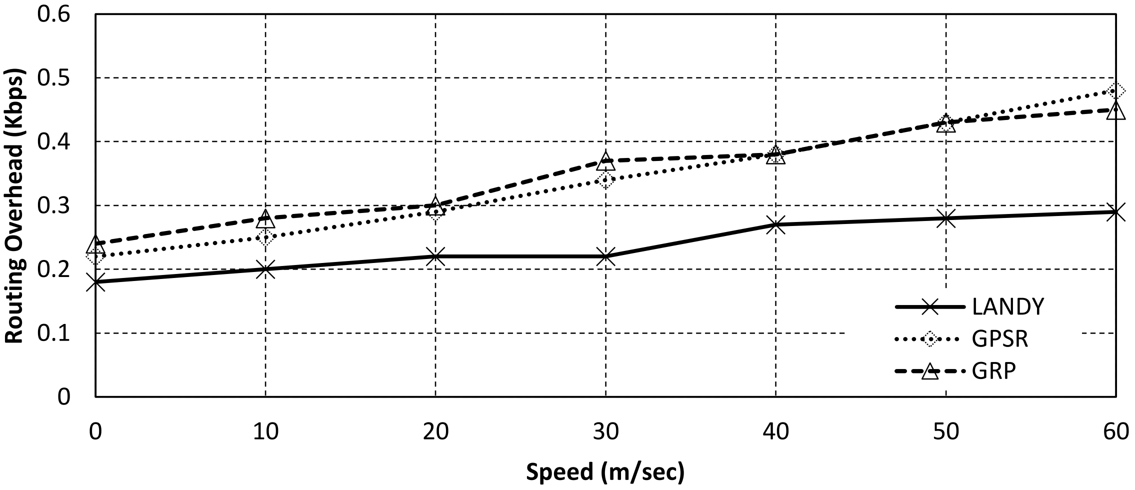
The routing overhead increases with the speed of the MNs. RPGM model gives minimum overhead as it supports the group movement and hence ensures more reachability.

In addition, with increased speed, each metric is deteriorating in some means. The GMM model has the highest routing overhead, and shortest average hop count. These results exist since the nodes in GMM model are often travelling near the centre of the simulation area, but the nodes in RPGM model can only change the direction until they reach the border of the simulation area.

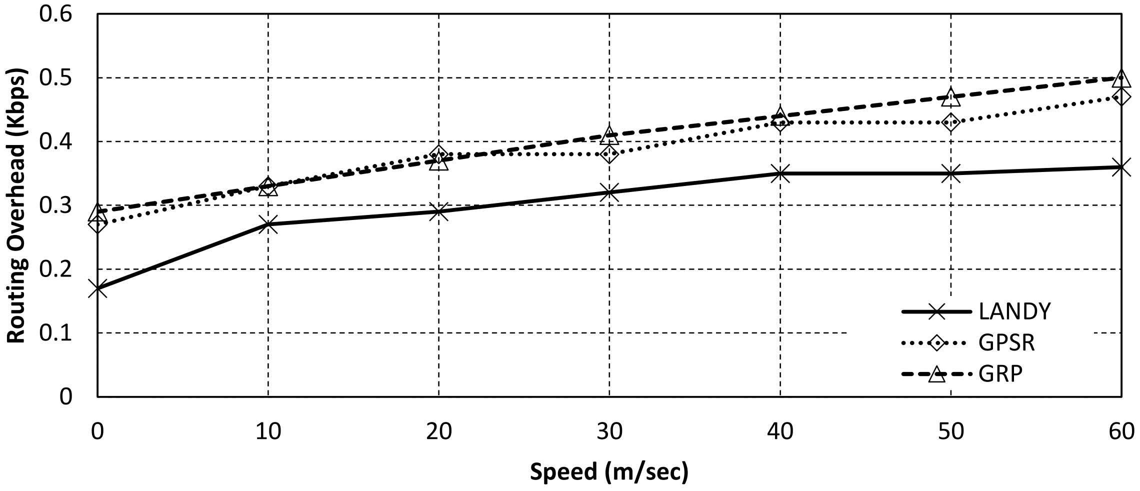
Therefore, the topology of the network can more easily be partitioned in GMM model than in that of RPGM. The percentage of packets received using LANDY is high even when mobility increases.

This result indicates, that these kinds of protocols will be desirable for high mobility networks. GPSR and GRP are dependent on periodic broadcast, which shows, a rather poor result. In-addition, a large byte overhead would mean a larger wasted bandwidth.

Many small control information packets, would mean that the radio medium on which packets are sent, is acquired more frequently. This would impact massively on the performance, power and network utilization.



(a) RPGM



(b) GMM

Figure 58. Routing Overhead vs. Speed – Scenario 2

The results for throughput are shown in Figure 59 and Table 25. The rate of packet throughput increases gradually, according to the increasing number of nodes in all protocols (GRP, GPSR and LANDY). The error bars indicate 95% confidence intervals.

As shown in Figure 59, there are a few differences between LANDY and GPSR in section of speed between 10 – 30 m/s , but differences increase in section 30 - 60 m/s. LANDY successfully increased the rate of packet throughput by as high as 24%.

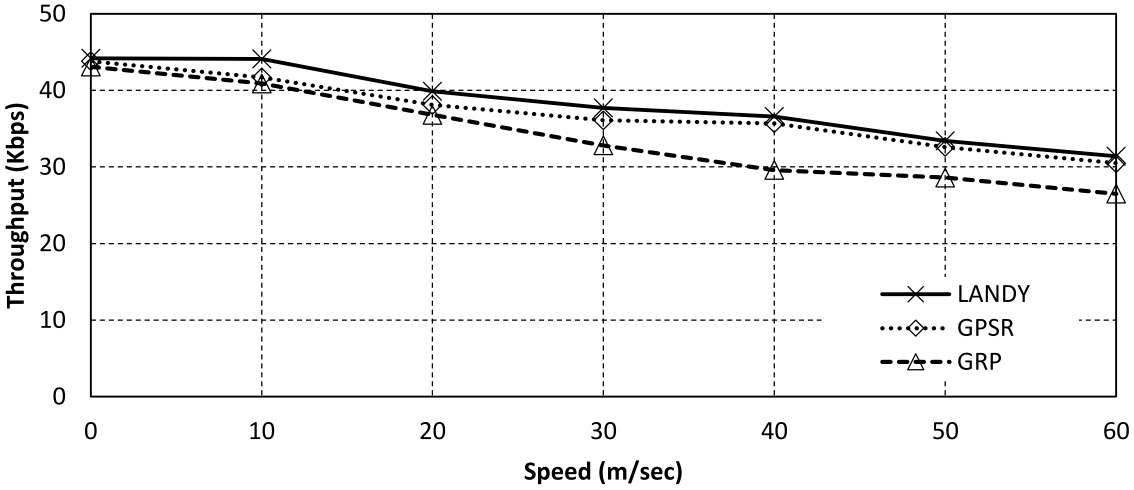
The reason why it is not a large performance improvement, is that the numbers of alternative routes are limited in the network, which comprises of a few nodes. Because the numbers of nodes are small and nodes are of wide distribution, the numbers of routes are limited, though a node searches for multiple routes.

When speed is varied from 0 to 20, the throughput values for LANDY, GRP and GPSR are stable. In overall, LANDY delivers the highest throughput and GPSR shows the lowest throughput. When maximum speed is varied, LANDY delivers the highest throughput and GPSR gives the lowest throughput.

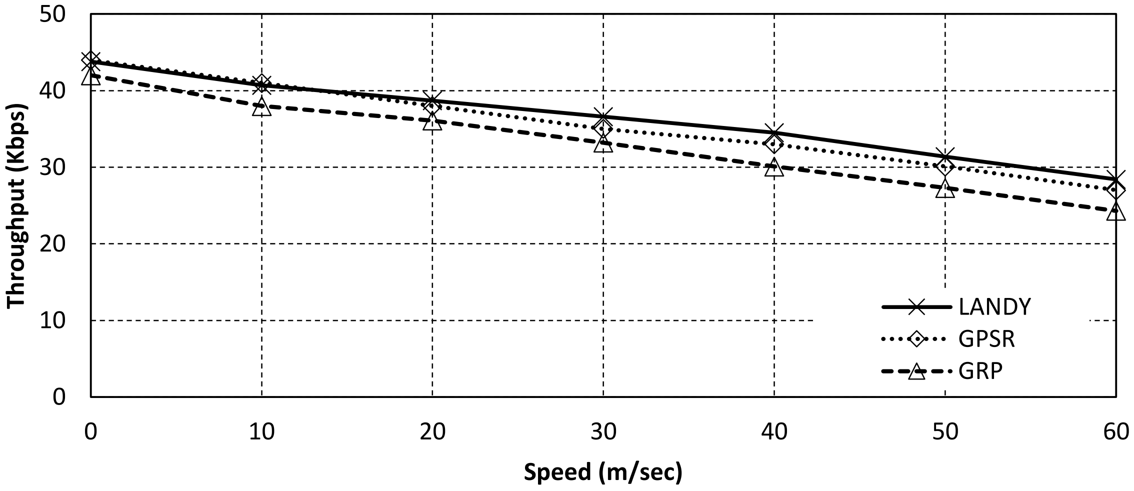
Also, the performance decrease is not large, but the performance decrease makes a distinct appearance when the speed is more than 30 m/s.

The more a node moves, the more nodes that consist of a link are changed, and link error can be generated frequently. By observing the packet throughput, GRP packet ratio is lower, due to link errors increasing as a result of faster node movement, but in LANDY, packet throughput is decreased little, when the maximum velocity of nodes is 60 m/sec.

The efficiency is 10%. This is logical, because large packet drops will, of course, produce lower throughput.



(a) RPGM



(b) GMM

Figure 59. Throughput vs. Speed – Scenario 2

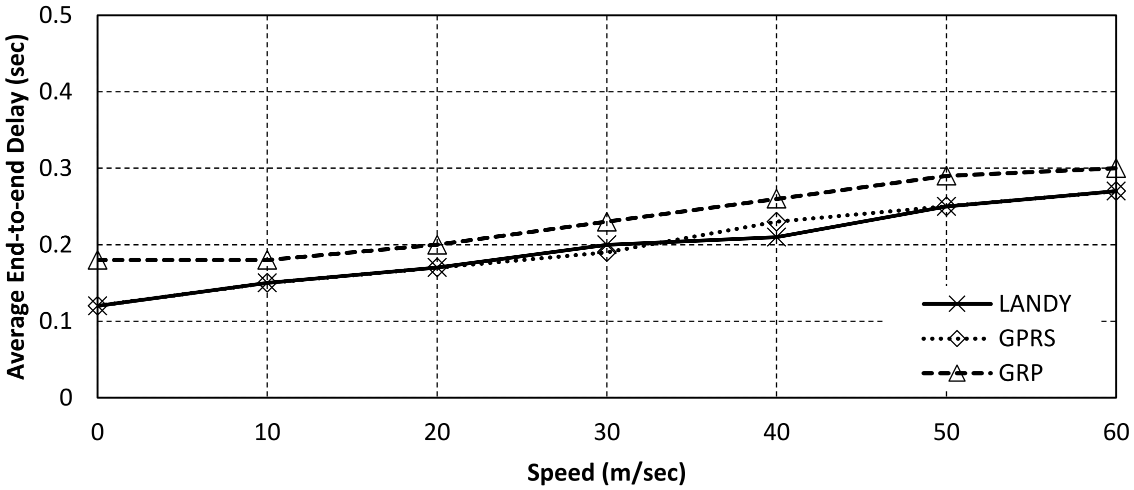
Figure 60 and Table 25 shows the average end-to-end delay of LANDY, GRP and GPSR. The error bars indicate 95% confidence intervals. Since LANDY searches the mobile node's future position instead of current position, it searches the path from the source to the destination faster than GPSR.

Thus, the average end-to-end delay of LANDY is lower than GPSR. When the number of nodes are between 10 and 30, GPSR has the highest average end-to-end delay, and it decreases for GRP and LANDY.

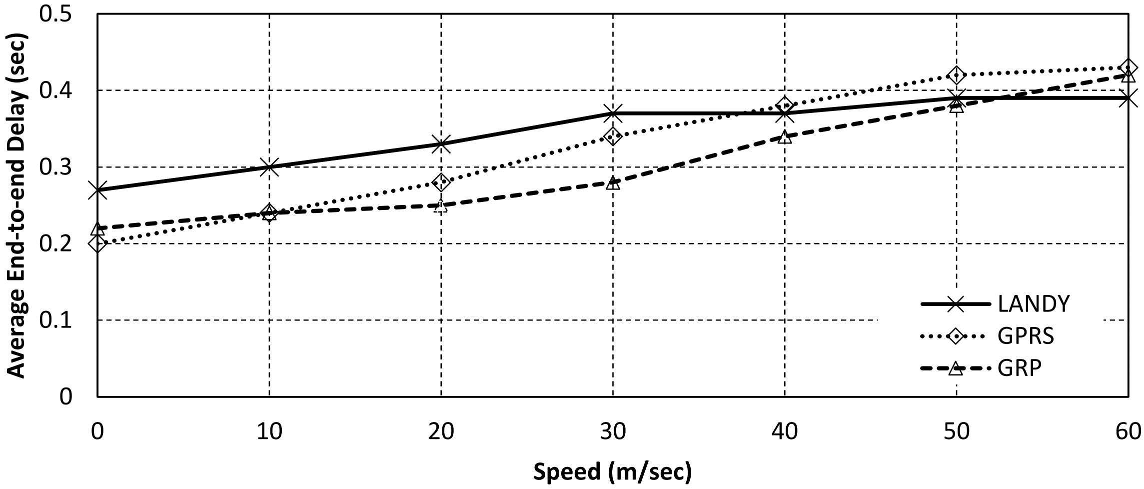
With increasing the number of nodes, the value of 'average end-to-end delay' for GPSR will be highest among the three protocols and lowest for LANDY. When the speed is 0, GRP has the highest average end-to-end delay.

When the speed is increased to 30, the slope for GRP decreases and it almost remains the same for GPSR and LANDY. When the speed is increased to 60, the value of the end-to-end delay increases for GRP, LANDY and GPSR. In overall, GRP has the highest average end-to-end delay and LANDY has the lowest reading.

The end-to-end delay time is massively affected when network speed is at a low rate. As a result of little or no mobility of nodes, error occurs in the entire path thus there is a greater chance that it searches paths consisting of the same nodes. In this case it cannot be effective, even if it selects a path taking mobility into consideration.



(a) RPGM



(b) GMM

Figure 60. Average End to end Delay vs. Speed – Scenario 2

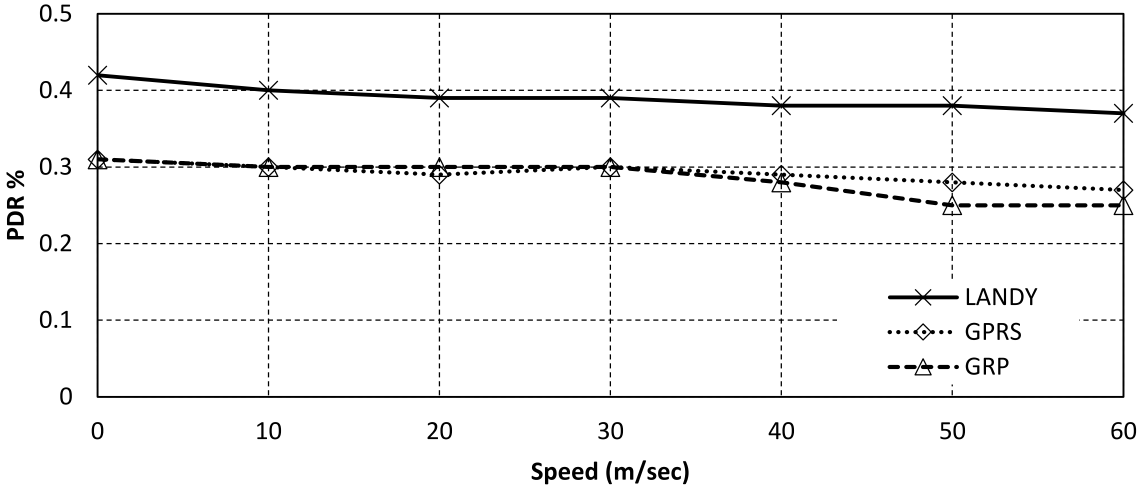
The packet delivery ratio results are shown in Figure 61 and Table 25 for LANDY, GPSR and GRP as a function of speed in the 500-node scenarios, respectively. The error bars indicate 95% confidence intervals.

Out of the three routing protocols, it is observed that LANDY performs better than the other two protocols in terms of packet delivery ratio. Results show that the packet delivery ratios in GMM, for the three protocols, do not have sudden changes when the speed of the mobile node increases. All three protocols perform well under GMM. LANDY has the highest packet delivery ratio when compared to GPSR and GPR.

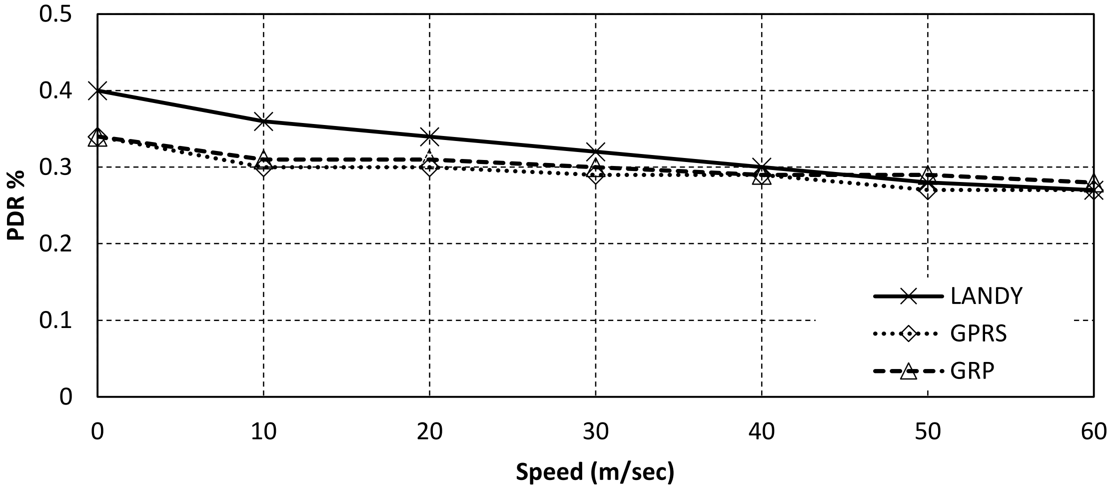
In GPR there is significant decrease in the packet delivery ratio when the speed of the MN increases. It is obvious that when the MN moves with greater speed, there are more chances for link breakage, resulting in less packet delivery ratio.

GMM mobility model gives the better packet delivery ratio for GRP and the RPGM gives the worst packet delivery ratio, because of the lower reachability. This ordering from the best to worst is roughly predicted by link changes.

LANDY is able to maintain high throughput for nearly all MMs, even as the speed increases. This is due to LANDY using locomotion, instead of current position, to find the mobile node's locomotion trajectory to predict the future position of MNs.



(a) RPGM



(b) GMM

Figure 61. PDR vs. Speed – Scenario 2

Table 25. Simulation Result - Scenario 2

(a) RPGM

Parameters	Routing protocols		
	LANDY	GRP	GPSR
Received	% 96.66	% 92.62	% 93.65
Send	44000	44000	44000
Dropped	467	1033	889
Throughput	38.1	36.9	34.04
Average end to end delay	0.28	0.3	0.28
Routing Overhead	0.29	0.44	0.48
PDR	0.38	0.26	0.28
Average hop count	3.52	4.34	3.97
Received packets	43533	42967	43111

(b) GMM

Parameters	Routing protocols		
	LANDY	GRP	GPSR
Received	% 95.77	% 91.4	% 93.38
Send	44000	44000	44000
Dropped	592	1204	926
Throughput	36.3	35.4	33
Average end to end delay	0.39	0.42	0.45
Routing Overhead	0.38	0.5	0.47
PDR	0.28	0.29	0.27
Average hop count	3.32	4.04	3.57
Received packets	43408	42796	43074

8.2.3. Scenario 3, with Some Relatively Slow Nodes and Some Very Fast Nodes

In scenario 3, we simulate an event or activity in region with lack of any communication infrastructure. MNs can communicate with each other, or relay to MNs that are attached on a vehicle, i.e. helicopter or car. Nodes can change positions regularly or remain semi-static.

The characteristics of this scenarios:

- Low movement, 50% of nodes. Seldom, they changed their position.
- High movement, 50% of the nodes. They changed their position frequently.
- Unstable connection.
- Network segregation.
- Long and short lasting links with fewer hops.
- Large number of obstacles within the event or activity region.
- Interference exists, but lower than scenario 1 and 2.
- Traffic is not focused, and it spreads across all the event region.
- There are 10 nodes moving with max speed in the region.
- There are 20 nodes (mobile and statics), that can communicate to the relays nodes.
- There are 100 MNs within sub-network, and they move randomly with various speed (0 – 60 m/s).

The Results of the routing overhead are shown in Figure 62 and Table 26. Results show, that LANDY has a smaller overhead than GPSR and GRP, as the number of link searches are small. This is because LANDY broadcast routing protocol packets proactively in a nearly constant interval.

GPSR have large number of routing control messages due to the topology changes. The routing overhead increases, with the speed of the MNs. RPGM model gives minimum overhead, as it supports the group movement and hence ensures more reachability.

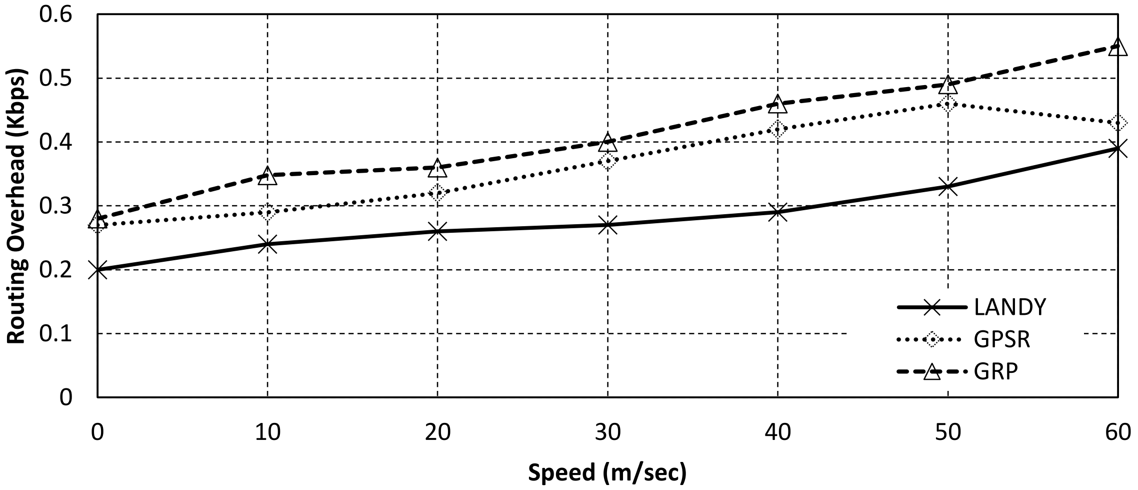
In addition, with increased speed, each metric is deteriorating in some means. The GMM model has the highest routing overhead, and shortest average hop count. The RPGM model is the reverse.

These results exist since the nodes in GMM model are often travelling near the centre of the simulation area, but the nodes in RPGM model can only change direction until it reaches the border of the simulation area.

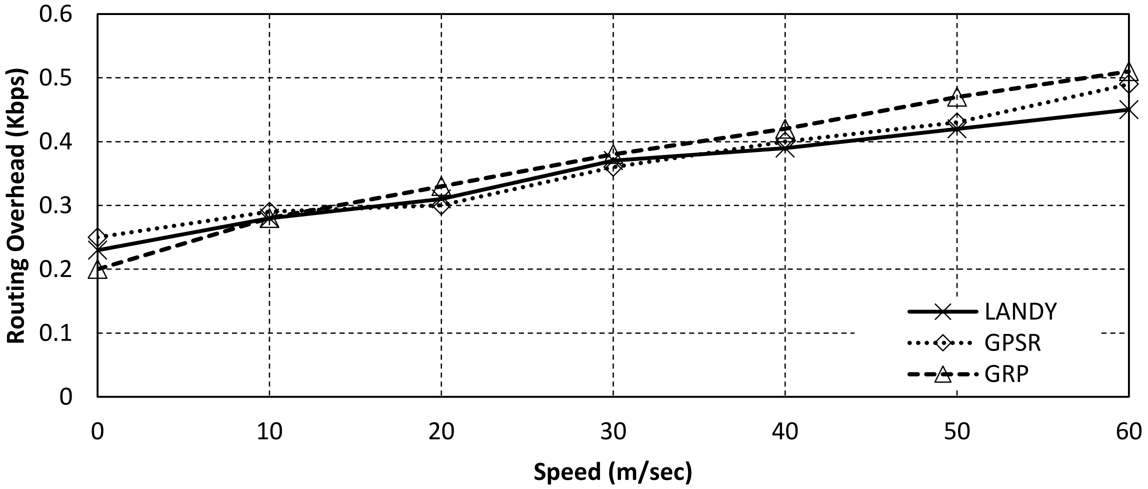
Therefore, the topology of the network can more easily be partitioned in GMM model than in that of RPGM. Moreover, the RPGM model through the probability of moving; a MN can go a longer distance before changing direction. It alleviates the sharp turnings and sudden stops; by changing the setting of MN.

The percentage of packets received, using LANDY, is high even when mobility increases. This result indicates, that these kinds of protocols will be preferred for high mobility networks. GPSR is dependent on periodic broadcast which show a rather poor result.

In-addition, a large byte overhead would mean a larger wasted bandwidth. Many small control information packets would mean, that the radio medium on which the packets are sent, is acquired more frequently. This would impact massively on the performance, power and network utilization.



(a) RPGM



(b) GMM

Figure 62. Routing Overhead vs. Speed – Scenario 3

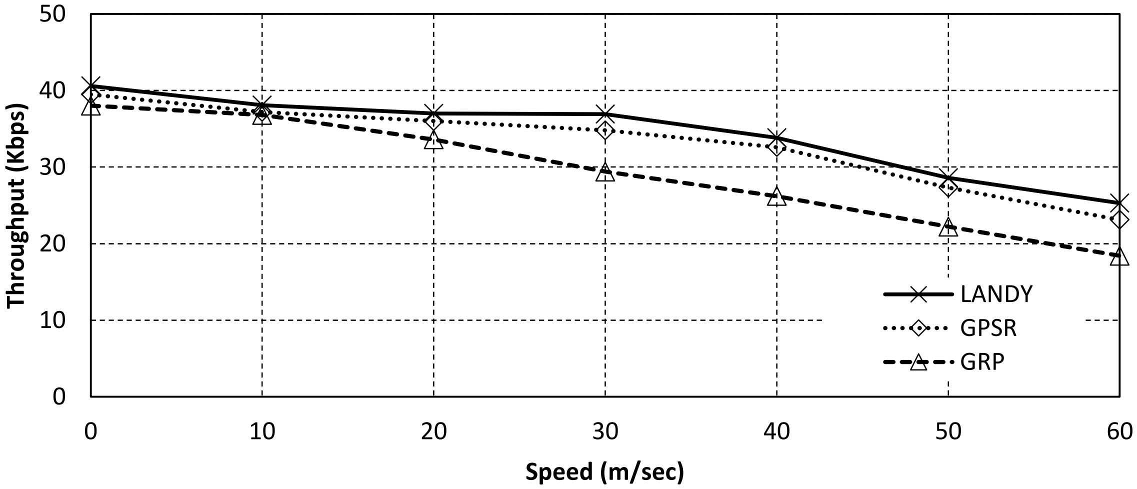
The results for throughput are shown in Figure 63 and Table 26. The rate of packet throughput increases gradually, according to the increasing number of nodes in all protocols (GRP, GPSR and LANDY). The error bars indicate 95% confidence intervals.

Results show few differences between LANDY and GPSR, in section of speed between 10 - 20 m/s, but differences increase in section 30 - 60 m/s.

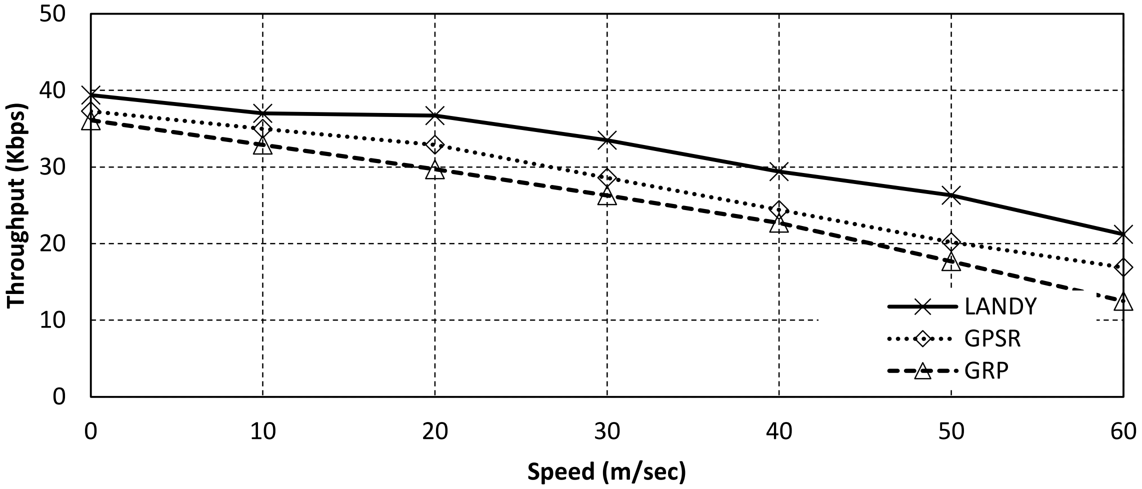
LANDY successfully increased the rate of packet throughput as high as 19 %. The reason why it is not a large performance improvement, is that the numbers of alternative routes are limited in the network which comprises of a few nodes. Also, the number of nodes are small and nodes are of wide distribution, and the numbers of routes are limited though a node searches for multiple routes.

In addition, the performance decrease is not large, but makes a distinct appearance when the speed is more than 20 m/s.

The more a node moves, the more nodes that consist of a link are changed, and link error can be generated frequently. GRP packet ratio is lower, due to link errors increasing as a result of faster node movement. But in LANDY, packet throughput is decreased little, when the maximum velocity of nodes is 60 m/sec. The efficiency is 7%. This is logical, because large packet drops will, of course, produce lower throughput.



(a) RPGM



(b) GMM

Figure 63. Throughput vs. Speed – Scenario 3

Figure 64 and Table 26 show the average end-to-end delay of LANDY, GRP and GPSR. The error bars indicate 95% confidence intervals. The end-to- end delay is lower in the case where more than two alternative routes can be selected, or many alternative routes.

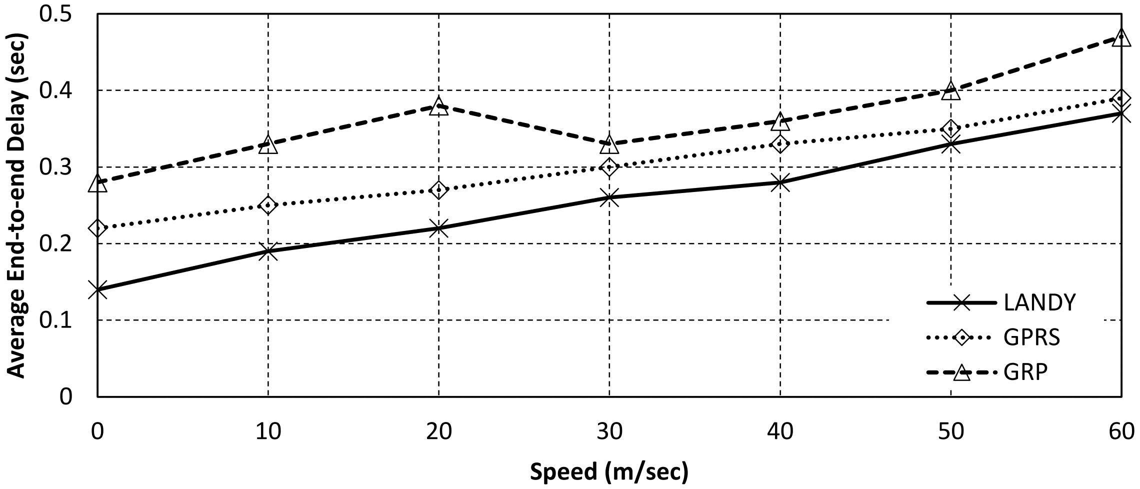
Since LANDY searches the mobile node’s future position instead of current position, it searches the path from the source to the destination faster than GPSR. Thus, the average end-to-end delay of LANDY is lower than GPSR.

When the number of nodes are between 10 and 50, GPSR has the highest average end-to-end delay, and it decreases for GRP and LANDY. With increasing the number of nodes, the value of average end-to-end delay for GPSR will be highest among the three protocols and it is lowest for LANDY.

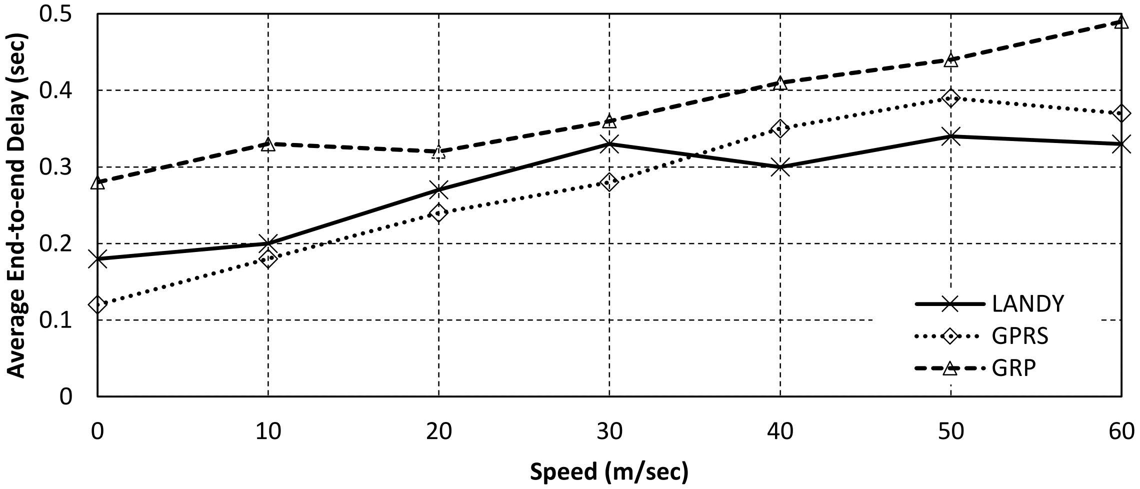
When the speed is 10, GRP has the highest average end-to-end delay. When the speed is increased to 20, the slope for GRP decreases and it almost remains the same for GPSR and LANDY. When the speed is increased to 60, the value of the end-to-end delay increases for GRP, LANDY and GPSR.

In overall, GPSR has the highest average end-to-end delay and LANDY has the lowest reading. The end-to-end delay time is massively affected when network speed is at a slow rate.

As a result of little or no mobility of nodes, error occurs in the entire path and so, there is a greater chance that it searches paths consisting of the same nodes. In this case, it cannot be effective even if it selects a path taking mobility into consideration.



(a) RPGM



(b) GMM

Figure 64. Average End to end Delay vs. Speed – Scenario 3

The packet delivery ratio results are shown in Figure 65 and Table 26 as a function of speed. The error bars indicate 95% confidence intervals. The delivery ratio of LANDY is higher than GPSR and GRP. The delivery ratio of LANDY remains high at all speeds.

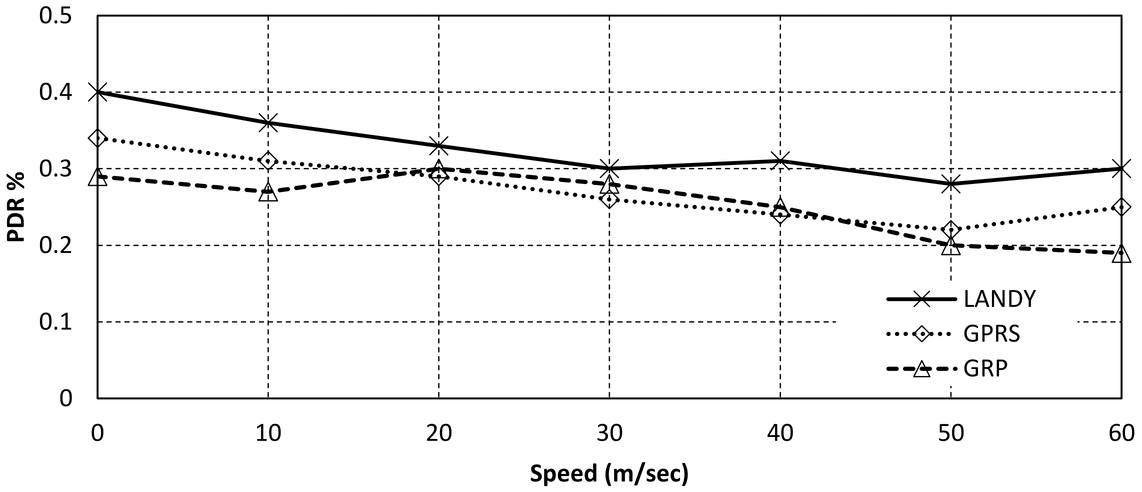
All the three protocols perform well under GMM. LANDY has the highest packet delivery ratio when compared to GPSR and GPR. In GPR there is significant decrease in the packet delivery ratio, when the speed of the MN increases.

It is obvious that when the MN moves with greater speed, there are more chances for link breakage which result in less packet delivery ratio.

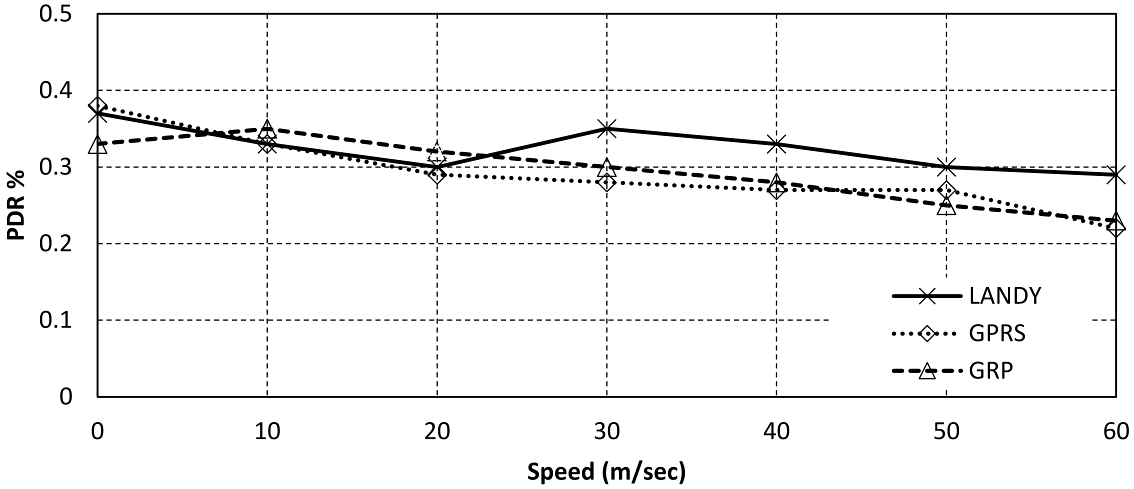
The throughput of GRP protocol depends entirely on the mobility model, and not on the speed of the MNs. GMM mobility model gives the better packet delivery ratio for GRP, and the RPGM gives the worst, because of the lower reachability.

This ordering from the best to worst is roughly predicted by link changes. LANDY is able to maintain high throughput for nearly all MMs even as the speed increases.

This is due to LANDY using locomotion instead of current position to find the mobile node's locomotion trajectory to predict the future position of MNs. It reduces the impact of the inaccuracy of neighbours' positions on the routing performance.



(a) RPGM



(b) GMM

Figure 65. PDR vs. Speed – Scenario 3

Table 26. Simulation Result - Scenario 3

(a) RPGM

Parameters	**Routing protocols**		
	LANDY	**GRP**	**GPSR**
Received	% 90.69	% 85.41	% 86.69
Send	53000	53000	53000
Dropped	2793	4375	3991
Throughput	34.3	32.9	29.2
Average end to end delay	0.38	0.49	0.38
Routing Overhead	0.28	0.41	0.36
PDR	0.3	0.19	0.26
Average hop count	2.92	3.78	2.73
Received packets	50207	48625	49009

(b) GMM

Parameters	Routing protocols		
	LANDY	**GRP**	**GPSR**
Received	% 90.20	% 85.35	% 89.09
Send	53000	53000	53000
Dropped	2939	4395	3273
Throughput	34.3	32.9	29.2
Average end to end delay	0.33	0.50	0.37
Routing Overhead	0.35	0.37	0.36
PDR	0.29	0.25	0.24
Average hop count	2.12	3.41	2.24
Received packets	50061	48605	49727

8.3. Chapter Summary

In the realistic scenarios performance testing, the following performance metrics were obtained from the two MMs (GMM, and RPGM): Throughput, PDR, routing overhead and average end-to-end delay. The realistic scenarios demonstrate how the protocols perform in certain conditions.

LANDY show the best performance results overall, where GPSR has a slightly higher packet overhead, but an overall good delivery ratio.

The percentage of packets received using LANDY is almost constant between 90 – 99% even when mobility increases. This result indicates that these kinds of protocols will be desirable for high mobility networks. GPR and GPSR are dependent on periodic broadcast, which show a rather poor result, only 85 – 89% of the packets are received when mobility is increased.

A higher sending rate causes the protocol to detect broken links faster, thus reacting faster; this leads to a slight increase in control packets, which affects the byte overhead. The increased send rate also sets demands on the send buffer of the routing protocol.

Congestion occurs and packets are dropped. The faster a routing protocol can find a route, the less time the packets have to spend in buffers, meaning a smaller probability of packet drops.

We have tested the protocols under high mobility speed range from 0 m/s up to 60 m/s. Our result conclude, that it is essential to use some support from the MAC-layer, to achieve a good performance in dynamic environment with high mobility.

As the simulation results show, the mobility of the network critically impact the performance of the protocols. Therefore, it is fundamental that the protocol should be able to detect and react fast to network changes and broken routes.

Result show poor performance by GRP in dynamic environment as the protocol is dependent on periodic update, and slow in detection of broken routes, plus takes time to converge.

In addition, the protocol does not scale well as result of the periodic broadcasts, which limits the protocol to small networks. LANDY scales well; the information that each node must store for each wanted destination is quite small, compared to GPSR and GRP that have to store whole source routes.

Overall, in all the scenarios LANDY outclasses the other two protocols, for the reasons of: High delivery rate, low delay and low message overhead, in terms of packets overhead.

CHAPTER 9. CONCLUSIONS AND FUTURE WORKS

9.1 Conclusions

We proposed a location based routing protocol for MANET. Our proposed lightweight protocol (LANDY), uses a localized routing technique which combines a unique locomotion prediction method and velocity information of MNs to route packets. The protocol is capable of optimising routing performance in advanced mobility scenarios, by reducing the control overhead and improving the data packet delivery.

Also the protocol addresses the issues which position based routing protocols encounter; the broadcast storm under ‘high node density, local minimum problem under low node density, and the geographically constrained broadcast of a service discovery message.

In addition, the approach of using locomotion prediction has the advantage of fast and accurate routing over other position based routing algorithms in mobile scenarios. Recovery with LANDY is faster than other location protocols which use mainly greedy algorithms, (such as GPRS), no signalling or configuration of the intermediate nodes is required after a failure. The key difference is that it allows sharing of locomotion and velocity information among the nodes through locomotion table.

We also proposed a new right hand rule algorithm (LAWAND) and new metric for measuring routing performance. The LAWAND right hand rule algorithm is developed to address these two issues (right hand rule may miss a perimeter path in a specific network graph, and right hand rule may follow a degenerate path) and always follows a proper perimeter when given the exact position of nodes. Using simple geometric forms we prove the new technique finds the shortest perimeter of an obstacle in the network.

The new metric for measuring routing performance is called Probability of communication process between active MNs, The measurement based on the assembled paths over randomised dynamic network topologies using “Sobol sequence” algorithm.

Simulation results show that LANDY`s performance improves upon other position based routing protocols.

9.2 Future Works

While we have shown the LANDY protocol reduces the control overhead, and improves routing performance in several types of sophisticated mobility scenarios, the LANDY can be enhanced with more features. In this research work, we assume the location service is available. It is desired to integrate location service into LANDY. Thus, LANDY can be implemented in the real mobile node more easily. LANDY can be extended to the 3D space. The '3D LANDY' can support the seamless and real-time communications in military application and the data traffic in the wireless sensor network in which the airborne MNs are necessary to relay communications.

Simulation experiments are widely used to evaluate MANET routing protocols. Similar to simulations of traditional wired networks, these experiments must model the network topology, network traffic, and the routing and other network protocols.

A tremendous amount of research remains to be done in the area of mobility models in ad hoc networks. Group Pursuit Models are of special interest for FCS applications, and have to be included in a comprehensive simulation.

It is important to investigate the application scenarios, to evaluate performance of MANET routing protocol. In other words, it is useful to simulate MANET routing protocols using the mobility model, which represents the application scenario more accurately.

Also it is important to examine the movements of MNs in the real world, to develop a new model that combines the best characteristics of major MANET mobility models, which can be used for performance evaluation of routing protocols in MANET.

LANDY can be extended to support more forwarding strategies. Some forwarding strategies perform better in a mobile network with high mobility, while some others perform better in a mobile network with low mobility. The LANDY will adjust the forwarding strategy adaptively, to get high throughput of data traffic.

In addition, comprehensive QoS investigation is required. The goal of QoS routing in MANET is to select routes with sufficient resources for data packets with QoS requirements to increase possibility that network will be capable of supporting and maintaining them. Finally, LANDY, with enhanced features, will be implemented in the real MNs and tested with real mobility scenarios.

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APPENDIX A: HEADER BLOCK CODE – LANDY ALGORITHM

```
/** Include files.                                **/

#include <ip_higher_layer_proto_reg_sup.h>

#include <ip_rte_v4.h>

#include <ip_rte_support.h>

#include <ip_addr_v4.h>

#include <manet.h>

#include <oms_dist_support.h>

#include <oms_pr.h>

#include <oms_tan.h>

#include <ip_dgram_sup.h>

#include "math.h"

#include "string.h"

#include "LC.c"

/* Define TTL */

#defineTTL                                        100

/* Define RNG */

#define        RNG                                     1

#define        NONRNG                                  0

/* Define constants for perimeter routing */

#define        PMODE                                   1

#define        GMODE                                   0

#define        LF                                      -1


/* Define constants for transition */

#define        BRD                                     0
```

```
#define         GEN                                         1
#define         LTTIMEOUT                                   10
#define         RTTIMEOUT                                   1000
/* Transition Macros                          */

#define               SELF_INTERRUPT (OPC_INTRPT_SELF == intrpt_type)

#defin STREAM_INTERRUPT           (OPC_INTRPT_STRM == intrpt_type)
e
#defin BROADCAST                                (OPC_INTRPT_SELF == intrpt_type &&
e                                               intrpt_code == BRD)
#defin GENERATE                                 (OPC_INTRPT_SELF == intrpt_type &&
e                                               intrpt_code == GEN)
#defin LTISTTIMEOUT (OPC_INTRPT_SELF == intrpt_type && intrpt_code > LTTIMEOUT &&
e      intrpt_code < RTTIMEOUT)
#defin              RTABLETIMEOUT    (OPC_INTRPT_SELF == intrpt_type && intrpt_code >
e                                                                      RTTIMEOUT)
/* Structure to hold information about a flow*/

typedef struct ManetT_Flow_Info

        {

        int                     row_index;

        OmsT_Dist_Handle        pkt_interarrival_dist_ptr;
        OmsT_Dist_Handle        pkt_size_dist_ptr; InetT_Address*
        dest_address_ptr;
        double                  stop_time;

        } ManetT_Flow_Info;

/* Structure of LC parameters */ typedef struct

        {

        double                  HELLO_start_time;

        double  datapkt_start_time; double
                HELLO_period;

        double  datapkt_interarrival; double      LT_timeout;

        double                  rtable_timeout;

        } LC_parameters;

/* Structure of route cache entry */
typedef struct {
        Objid                   dest;
        Objid                   nexthop;
        double                  timer;
        } rtentry;
```

```
/* Structure of packet route */ typedef struct

        {

        int                     rt_length;
        Objid                   rt [TTL];
        } routes;

/* Structure of neighbor nodes */
typedef struct {
        LCE*                    LCE_ptr;
        int                     rng_mark;
        double                  angle;
        } neighbor;
/* Statistics variable declaration   */ static
int ctrl_pkt_sent_count = 0; static int
data_pkt_sent_count = 0; static int
data_pkt_recv_count = 0; static int
route_length = 0; static double
avg_route_length = 0.0; static double
delivery_ratio = 0.0;

/* Define constants            */

static const double        pi=3.141592653;

/** Function prototypes.                            **/

SV          LC_sv_init (void);
SV          LC_register_self (void);
SV          LC_sent_stats_update (double pkt_size);
SV          LC_received_stats_update (double pkt_size);
SV          LC_packet_flow_info_read (void);
SV          LC_generate_packet_copy (void);
SV          LC_packet_destroy (void);

SV          LC_packet_receive (void);
SV          LC_generate_packet (void);
SV          LC_broadcast_packet (void);
SV          LC_HELLO_destroy (Packet*);
SV          LC_datapkt_receive (Packet*);
SV          LC_location_update (void);
SV          LC_LCE_init (void);

SV          LC_parameters_init (void);
SV          LC_LCE_print (LCE* LCE_ptr);


SV          LC_LT_update (LCE* LCE_ptr);
SV          LC_LT_print (void);
SV          LC_LT_timeout (int intrpt_code);
```

```
SV              LC_rt_update (Objid dest, Objid nexthop);
SV              LC_rt_timeout (int intrpt_code);
SV              LC_rt_print (void);
SV              LC_rtentry_print (rtentry* rtentry_ptr);

static Objid     LC_search_nexthop (Objid dest, LCE* LCE_ptr);
static double LC_dist (LCE* LCE_ptr1, LCE* LCE_ptr2); Static double
LC_dist_future (LCE* LCE_ptr1, LCE* LCE_ptr2);



/** Function prototypes.                              **/

SV              LC_BP_sv_init (void);
SV              LC_BP_register_self (void);
SV              LC_BP_sent_stats_update (double pkt_size);
SV              LC_BP_received_stats_update (double
                pkt_size);
SV              LC_BP_packet_flow_info_read (void);
SV              LC_BP_generate_packet_copy (void);
SV              LC_BP_packet_destroy (void);

SV              LC_BP_packet_receive (void);
SV              LC_BP_generate_packet (void);
SV              LC_BP_broadcast_packet (void);
SV              LC_BP_HELLO_destroy (Packet*);
SV              LC_BP_datapkt_receive (Packet*);
SV              LC_BP_location_update (void);
SV              LC_BP_LCE_init (void);

SV              LC_BP_parameters_init (void);
SV              LC_BP_LCE_print (LCE* LCE_ptr);


SV              LC_BP_LT_update (LCE* LCE_ptr);
SV              LC_BP_LT_print (void);
SV              LC_BP_LT_timeout (int intrpt_code);

SV              LC_BP_rt_update (Objid dest, Objid nexthop);
SV              LC_BP_rt_timeout (int intrpt_code);
SV              LC_BP_rt_print (void);
SV              LC_BP_rtentry_print (rtentry* rtentry_ptr);

                 LC_BP_search_nexthop (Objid dest, LCE*
static Objid     LCE_ptr);
static double LC_BP_dist (LCE* LCE_ptr1, LCE* LCE_ptr2); Static double
LC_BP_dist_future (LCE* LCE_ptr1, LCE* LCE_ptr2);



/** Function prototypes.                              **/
```

```
SV              CELL_sv_init (void);
SV              CELL_register_self (void);
SV              CELL_sent_stats_update (double pkt_size);
SV              CELL_received_stats_update (double
                pkt_size);
SV              CELL_packet_flow_info_read (void);
SV              CELL_generate_packet_copy (void);
SV              CELL_packet_destroy (void);

SV              CELL_packet_receive (void);
SV              CELL_generate_packet (void);
SV              CELL_broadcast_packet (void);
SV              CELL_HELLO_destroy (Packet*);
SV              CELL_datapkt_receive (Packet*);
SV              CELL_location_update (void);
SV              CELL_LCE_init (void);

SV              CELL_parameters_init (void);
SV              CELL_LCE_print (LCE* LCE_ptr);


SV              CELL_LT_update (LCE* LCE_ptr);
SV              CELL_LT_print (void);
SV              CELL_LT_timeout (int intrpt_code);

SV              CELL_rt_update (Objid dest, Objid nexthop);
SV              CELL_rt_timeout (int intrpt_code);
SV              CELL_rt_print (void);
SV              CELL_rtentry_print (rtentry* rtentry_ptr);

                 CELL_search_nexthop (Objid dest, LCE*
static Objid     LCE_ptr);
static double CELL_dist (LCE* LCE_ptr1, LCE* LCE_ptr2); Static double
CELL_dist_future (LCE* LCE_ptr1, LCE* LCE_ptr2);


static LCE* LC_intersection_exist (LCE* LCE_ptr1, LCE* LCE_ptr2, LCE* LCE_ptr3, LCE*
LCE_ptr4);

static LCE* LC_BP_intersection_exist (LCE* LCE_ptr1, LCE* LCE_ptr2, LCE* LCE_ptr3, LCE*
LCE_ptr4);


static LCE* CELL_intersection_exist (LCE* LCE_ptr1, LCE* LCE_ptr2, LCE* LCE_ptr3, LCE*
LCE_ptr4);
```